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CRITICAL REVIEW OF AIR POLLUTION DOSE-EFFECT FUNCTIONS

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Enviro Control, Incorporated

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CRITICAL REVIEW OF
AIR POLLUTION DOSE-EFFECT FUNCTIONS

FINAL REPORT
Under Contract EQ5-AC012

March 1976

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Performed for:

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FOREWORD

This Final Report is published in fulfillment of Council for Environmental Quality Contract No. EQ5AC012, entitled "Assessment and Enhancement of the Utility of Air Pollution Dose-Effect Functions." The study was co-sponsored by the U.S. Environmental Protection Agency, Office of Research and Development.

The material in this volume is organized under five chapters and an appendix, as follows:

- Introduction
- Survey of State of Knowledge
- Analytical Methodology
- Analysis of Selected Functions
- Research Needs
- Appendix: Demonstration of the Utility of Damage Functions

This foreword and an executive summary complete the organization.

The first chapter introduces the major concepts and issues of this study and covers the role and nature of dose-effect functions and their merits and lacks, as well as the purpose, objectives, scope, and organization of the study. The second chapter provides a brief, succinct, but critical survey of the investigations leading to the development of significant dose-effect functions. The methodology chapter discusses the various problems and issues inherent in the development of dose-effect functions, including determination of ambient levels, exposure and effects, types of studies, establishment of dose-effect relationships, and presentation of results. The fourth chapter presents a critical analysis of dose-effect functions pertaining to effects of sulfur dioxide and particulates on human mortality, injury to tobacco leaves by oxidants, and corrosion of zinc by sulfur dioxide and moisture. The last chapter addresses needs for future data collection, development, and investigation, in light of the findings of this study.

This report is designed to assist the investigator of air pollution exposure effects with the development of a valid and useful dose-effect function and to provide the user of these functions with an introduction to their potential and limitations. It has little to offer to the expert in this field. Its major accomplishment is less the advancement of any specific aspect of the state of the art than the assemblage and presentation of much pertinent information in a systematic and readable fashion.

The first attempt to treat a field of inquiry of such broad scope under one cover can not possibly please everyone and is bound to displease some, perhaps severely. Pet views and favored findings will be found flouted, or worse, ignored. Offensive definitions and despised results will be viewed as excessively flaunted. Some chapters will be regarded as too verbose, and others as too skimpy. All these criticisms and others have transpired even in the valued comments of our own Technical Review Panel. Yet, the effort had to be undertaken, and the report had to be written. The test of its success will be its utility to those readers for whom it was designed.

The work described here was performed by Dr. Alex Hershaft with the assistance of Mr. G. Bradford Shea and Mr. John D. Morton, all of Enviro Control. Other contributors included Dr. James S. Whang of Enviro Control and Dr. Eugene P. Seskin of the National Bureau of Economic Research. Ms. Anita Calcote was responsible for typing and production of the report.

Critical review of the interim drafts and numerous valuable comments were provided by a distinguished Technical Review Panel composed of six recognized authorities on dose-effect functions, though the responsibility for any errors of omission or commission rests exclusively with the principal author. Their names, affiliations, and specialties are as follows:

- Dr. Robert W. Buechley, Statistical Epidemiologist, School of Medicine, University of New Mexico
- Health effects of air pollutants

- Dr. Lester B. Lave, Head, Department of Economics, Carnegie-Mellon University
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 - Effects of air pollutants on vegetation
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 - Disease effects of air pollutants
- Mr. John E. Yocom, Vice President, The Research Corporation of New England
 - Effects of air pollutants on materials.

Finally, this entire effort would not have been possible, but for the foresight, initiative, and helpful guidance of Dr. James J. Reisa, the CEQ Project Officer. Dr. William C. Nelson of the U.S. EPA's National Environmental Research Center at Triangle Park, North Carolina, was the cognizant U.S. EPA Project Officer.

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EXECUTIVE SUMMARY

The discussion, analysis, and conclusions of this report are summarized here under the headings of introduction, survey of state of knowledge, analytical methodology, analysis of selected functions, and research needs.

A. INTRODUCTION

This section introduces the major concepts and issues underlying the subject matter of this report. The topics covered include the role and nature of dose-effect functions, nature and effect of air pollutants, and the purpose, objectives, scope, and organization of the report.

1. Overview

Damages associated with air pollution may take the form of increased mortality and incidence and prevalence of disease, diminished enjoyment of the outdoors, reduced crop yields, more frequent maintenance and replacement of exposed materials, and other, less well identified losses. Legislators, planning officials, and other environmental decision makers are frequently faced with the decision of how much to reduce pollutant levels in the light of the associated direct costs of pollution control and secondary economic effects. Although benefit /cost analysis is not an exact science and the results are difficult to express in monetary terms, the inherent process of logical and systematic scrutiny can contribute substantially to the ability of decision makers to allocate more efficiently the limited cleanup resources.

There exists an interactive relationship among pollutant emissions, ambient air quality, damages and benefits, and policy decisions. A damage, or dose-effect, function is the quantitative expression of a relationship between exposure to specific pollutants and the type and extent of the associated effect on a target population. In plotting such a function, the ordinate may represent either the number of individuals affected or severity of effect, whereas the abscissa indicates the dosage in terms of time and ambient concentration. In reporting a damage function, one needs to specify the pollutant, the dose rate, the effect, and the target population.

The data required to develop dose-effect functions may be obtained through epidemiological, field, clinical, toxicological, or laboratory investigations. The principal techniques for analyzing the relationship between exposure and effect indices in epidemiological and field studies are known as cross tabulation, multivariate regression, and distribution-free analysis. In employment of these techniques, it is important to isolate or control the influence of cofactors and covariates. Controlled experiments, such as toxicological and laboratory investigations, are used to test observations gained from epidemiological and field studies.

Dose-effect functions can serve as valuable instruments in the popular conceptualization of the threats posed by environmental pollution, in determination of an optimal extent of pollution abatement, and in development of a more rational allocation of limited resources. However, these functions suffer from some important drawbacks that diminish their usefulness. They are frequently based on insufficient data, they force a quantitative interpretation on relationships that cannot be validly quantified, and they fail to account properly for synergistic or antagonistic relationships. The major problem areas are collection and retrieval of reliable ambient air quality data, selection of exposure indicators, selection of representative populations, determination of effects, establishment of causal relationships, and presentation of results.

2. Purpose and Scope

The purpose of this effort is to assess and demonstrate the utility and potential applications of existing and emerging air pollution dose-effect functions. The specific objectives are to assess the state of the art in developing air pollution dose effect functions, to interpret and communicate the significance of available and emerging functions, and to suggest improvements in analytical methodology and define new areas for study.

The effort was organized under five tasks presented in four chapters and an appendix, as set forth below:

- Prepare survey of literature on dose-effect functions (Chapter II)
- Prepare survey of methodology (Chapter III)

- Analyze selected dose effect functions (Chapter IV)
- Discuss future needs and projects (Chapter V)
- Prepare demonstration for CEQ annual report (Appendix).

The pollutants included in this study are total suspended particulates, sulfur dioxide, nitrogen dioxide, photochemical oxidants, carbon monoxide, hydrocarbons, sulfates, nitrates, and fluorides. Only physical and biological, as distinct from economic, effects are examined and both chronic and acute responses are considered. The effect categories encompass health effects, vegetation damage, materials damage, and such other effects as aesthetic impairment and climatic changes.

B. SURVEY OF STATE OF KNOWLEDGE

The effects of air pollutants have been addressed by numerous investigators during the past decade. However, many of these studies display limited applicability, insufficient concern for impact of covariates, or other flaws that frustrate aggregation of the results into a valid and meaningful dose-effect function. A number of selected studies are surveyed here under five categories of effects: human health, vegetation, materials, aesthetics and weather, and effects of water pollutants.

1. Effects on Human Health

Effects of air pollutants on human health have received the most attention because of their relatively high social importance. The most generally useful relationships between exposure to air pollutants and health effects have been obtained from epidemiological studies. Clinical and toxicological observations have not been included in the survey because of the difficulty of extrapolating their results to the general human population. Studies that do not formulate meaningful quantitative relationships, fail to control for relevant covariates, or merely report on catastrophic air pollution episodes have also been excluded.

The major pollutants investigated are sulfur oxides and particulates, nitrogen oxides, photochemical oxidants, carbon monoxide, and unspecified air pollutants. The principal effects are mortality and morbidity, but each of these may be further characterized by specific diseases, such as respiratory and cardiovascular dysfunctions, neoplasms of the respiratory and gastrointestinal tracts, chronic nephritis, and impaired fetal development and mental function. Indicators of morbidity include absenteeism, hospital admissions and residence days, doctors' visits, and personal histories.

A number of important cross-sectional epidemiological studies have compared the effects of sulfur oxides and particulates on populations of various metropolitan areas. The effects of nitrogen oxides on human health have received relatively less attention, perhaps because of the difficulty of measuring ambient concentrations and the lack of reliable historical data. Only two studies of the effects of photochemical oxidants on human health

were found to meet all of the selection criteria. Effects of carbon monoxide on human health have been investigated almost entirely by toxicological experiments and clinical observations in conjunction with occupational exposure. Finally, several useful investigations were conducted on the effects of other pollutants or non-specific air pollution.

2. Damage to Vegetation

Concern for air pollution damage to vegetation has received renewed impetus from the recent discovery of heretofore unsuspected high oxidant levels in rural areas and the completion of investigations indicating substantial crop losses at these levels. In the past, there had been relatively little interest in coordinating the efforts of various investigators or in setting uniform standards and conditions that would permit some aggregation or comparison of the results of different studies.

The principal pollutants implicated in substantial damage to vegetation are sulfur dioxide, oxidants, nitrogen oxides, acid rain, and fluorides. Determination of effects on crops and forests is severely handicapped by the virtual lack of monitoring stations in rural areas. Effects of air pollutants on vegetation exhibit wide variations among the various species and as a result of different genetic and environmental conditions. The latter includes stage of growth, general viability and vigor, temperature, humidity, amount of insolation, soil moisture and acidity, and availability of nutrients. In the past, determination of effects was based largely on measurement of the extent of leaf injury, but more recently, it has been realized that substantial yield losses can occur even in the absence of significant leaf injury.

The state of development of consistent and broadly applicable dose-effect functions in the area of vegetation damages is considerably less advanced than in the areas of health effects or material damages. The fault may be attributed to the scarcity of air quality records in rural areas, some lack of foresight and coordination in the design of investigations and presentation of results, but most of all to the broad variety of target species and the ensuing variability of effects.

Early studies identified sulfur dioxide as the primary factor in air pollution damage to vegetation, but more recent investigations have examined the effects of acid rain and mist. Effects of photochemical oxidants, including ozone, have attracted a great deal of attention in the wake of the recent discovery of high oxidant levels in rural areas. Investigations of the effects of nitrogen oxides have suffered from difficulties of measurement, rapid fluctuations of ambient levels due to chemical reactions, and the synergistic effects with sulfur dioxide and oxidants.

3. Damage to Materials

Investigation of the effects of air pollutants on materials permits the control of both exposure and the make-up of the target population. Nevertheless, useful dose-effect functions in this area are largely confined to representations of the corrosion of metals by sulfur oxides and the soiling of exposed surfaces by particulates. Other pollutants studied include particulates, nitrogen oxides, and oxidants. Other target populations are paper, textiles, leather, paints and dyes, rubber, plastics, metals, ceramics, and stone.

Effects of long-term exposures have been determined by exposing test panels to ambient conditions for long periods of time. The results of these field studies have been flawed by poor ambient level measurements and failure to account for other pertinent environmental variables. Laboratory studies have attempted to determine short-term effects by subjecting test panels to elevated pollutant concentrations. Recent laboratory experiments have used more realistic concentrations.

4. Other Effects of Air Pollution

Other effects of air pollutants include aesthetic and meteorological effects. Aesthetic effects may take the form of reduced visibility or offensive odors. Meteorological effects involve changes in precipitation patterns and in the mean temperature of the earth's atmosphere. Aesthetic effects have been measured in monetary terms by assessing the people's willingness to pay for pollution control leading to a reduction of the offensive condition.

5. Effects of Water Pollution

Effects of water pollution have received less quantitative scrutiny than effects of air pollution, perhaps because loss of recreation, the largest effect, is too difficult to measure, and because most effects are attributable to different combinations and concentrations of various pollutants. Dose-effect functions have been developed for the effects of various pollutants on fish and other aquatic organisms, as well as on household plumbing fixtures.

C. ANALYTICAL METHODOLOGY

In spite of the potential importance of dose-effect functions and the amount of effort that has gone into generating the necessary data, the methodology for developing these functions and handling of the attendant problems and uncertainties are still in their infancy. This section traces the methodology through the progressive stages of study design measurement of ambient levels, determination of exposure, determination of effect, estimation of functional relationships, and presentation of results.

1. Design of Study

Design of the study is a crucial stage in the dose-effect development process, for it sets the pattern for much of the subsequent effort and determines the usefulness of the results. The major decisions involve selection of pollutants and measures, effect and measures, population at risk, time frame and geographic area, and type of study.

Selection of pollutant typically requires also some attention to pollutants that may be acting synergistically or antagonistically toward the pollutant of interest. Selection of measures involves not only the specific units of measurement, but also the type of measures (averages or peaks) and periods of measurement.

Similarly, selection of effect entails decisions on types of effect, and units and periods of measurement. Selection of population at risk, geographic area, and time frame are usually governed by availability of data and funds, in addition to the usual criterion of intended use.

Characterization of the human population at risk is usually limited to sex, race, and age, because other personal and socio-economic traits are more difficult to determine and they fragment the size of the sample. In the case of vegetation and materials, characterization of the population at risk takes the form of specification of the plant species and precise material composition, respectively. The importance of these characterizations lies in their impact on the susceptibility or sensitivity of the population at risk to the effects under study.

In selecting the type of study, one must first choose the type of approach (i.e., epidemiological or field, clinical, toxicological or experimental, or survey). If the epidemiological or field approach is selected, additional decisions must be made on whether the study should be longitudinal (time-series) or cross-sectional (different communities) and retrospective or prospective. Personal surveys can provide amplification of health effects data and reporting of less tangible effects.

2. Determination of Ambient Levels

The principal problem areas in the determination of ambient air quality levels are collection of sufficient data, selection of optimal sampling modes and valid analytical techniques, averaging and aggregation of concentration levels over time and space, and determination of ambient levels in the immediate proximity of the subjects from measurements at monitoring stations.

Collection of sufficient air quality data to determine with some confidence the ambient levels of a community requires a large number of stations collecting frequent readings on several pollutants and a massive commitment to data handling well in excess of the present level. This is the case, because the various point, line, and area sources discharge intermittently into a fluid medium, where the pollutants undergo various transport, dilution, and chemical transformation processes.

Sampling mode is important if one is attempting to study acute effects of air pollution, which requires measurement of intensity and duration of concentration peaks, rather than daily or monthly averages. Valid analytical techniques are those that are specific for the pollutant under study and reasonably accurate. The data must be sufficiently disaggregated over time and space to serve the design requirements of the study.

3. Determination of Exposure

Exposure is typically measured as some formulation of ambient concentration levels and their duration which may be expressed as "dosage" (integral of the ambient concentration and its duration as recorded at the

monitoring station) or "dose" (that portion of dosage instrumental in producing the observed effect). The difference between these two quantities may be accounted for by non-uniformity of the pollution field, mobility of subjects, shielding of subjects, and uptake characteristics. An important concept in the determination of exposure is the dose rate, or the variation of concentration level with time.

Exposure of stationary subjects, i.e., plants and most materials, is determined by the dynamics of the pollution field alone. However, for humans, animals, and other moving subjects, exposure is governed also by their own mobility. The need to consider the effect of shielding by building enclosures is underlined by the fact that an overwhelming portion of the U.S. population spends some 85 percent of its life indoors. Humans and animals, termed "active" receptors, take up pollutants through inhalation and swallowing, whereas uptake by plants and stationary material objects, the "passive" receptors, is governed more by meteorological conditions, position of the affected surface, and the presence of any protective mechanisms.

The most common measures of exposure are average concentration during a given period of time or the amount of time at a given level of ambient concentration. Other common measures include the frequency, duration, and/or intensity of peaks or instances when ambient concentration exceeds a certain level, as well as dosage, i.e., the integral of concentration and time. The construction of composite indices, made up of several measures of exposure, has been suggested. Measurements of the actual dose are not generally feasible, nor necessarily useful, because the difference between dose and the measure employed becomes implicit both in the development and the interpretation of the dose-effect function.

4. Determination of Effect

The effect of air pollutants on a given target population is defined in terms of the type of effect, its duration, reversibility, sensitivity of the target population, specificity, threshold and saturation, and measures of effect. Terms commonly used to denote effect include

response, injury, and damage. Duration of damages provides for their classification as chronic or acute. Reversibility refers to the ability of the subject to repair the damage and restore the function upon cessation of exposure.

The type and severity of effects are governed in large measure by the sensitivity and susceptibility of individual members or classes of the target population. In assessing specific effects, it is very important to isolate the influence of any cofactors (factors that act simultaneously, synergistically, or antagonistically with the pollutants), and mimics (factors that simulate the effect of certain pollutants).

The effects of air pollutants on human health may be classified as body burden, uncertain physiological changes, adverse physiological changes, morbidity, and mortality. Morbidity, including the incidence and prevalence of disorders, and mortality are by far the most commonly investigated types of health effects. In most cases, the data are broken down by specific disorder and by characteristics of the target population.

Effects of air pollutants on vegetation are manifested through physiological changes, various types of injury to leaves and other parts of the plant, reduced yield, reduced plant growth, and death. The most remarkable feature of past measurements of air pollutant effects on vegetation is their wide diversity which frustrates attempts at verifying, comparing, or aggregating the results of different studies. The major cofactors in effect of air pollutants on vegetation are the meteorological conditions, such as humidity, precipitation, insolation, temperature, and air turbulence, as well as soil moisture and nutrient content.

Effects of air pollutants on materials are rather well defined in comparison with health or vegetation effects, because of greater uniformity of samples, simpler damage mechanisms, and higher reproducibility of results. The principal effects may be classified as soiling and coating of exposed surfaces, corrosion of metals, degradation of textiles, rubber, and masonry surfaces, and fading of dyes. The important cofactors affecting the attack of materials include humidity, temperature, sunlight, and air turbulence.

5. Estimation of Functional Relationship

The more common statistical techniques for defining the quantitative relationship between exposure and effect are cross tabulations or simple correlations, multivariate regression analysis, and distribution-free analysis. The difficulty with the first method is that a host of other factors are allowed to vary across populations, so that it is usually not feasible to isolate the effect of pollutants alone. Multivariate regression analysis permits statistical control over interfering factors and provides a rapid estimate of the degree of association between a number of independent variables and the dependent variable. Distribution free analysis requires fewer assumptions about the distribution of the variables, but its use is more time consuming and requires greater intervention of human judgment.

The principal covariates in air pollution effect studies are other pollutants, other types of exposure, meteorological conditions, personal and socio-economic characteristics of the target population, and timing. An ideal investigation of the specific effects of an air pollutant would hold constant, or control all likely covariates. This can be accomplished, respectively, by judicious design of the investigation, or by statistical techniques.

6. Presentation of Results

The classical representation of the relationship between exposure and effect takes the form of a sigmoid, or S-shaped curve. The ordinate may represent either the number of individuals affected or severity of effect, whereas the abscissa indicates the dosage, in terms of time at the given ambient concentration, or ambient concentration over a fixed period of time. Nearly all dose-effect functions reviewed in this study represent some variation on this basic relationship.

The most general type of relationship between exposure and effect is "associative", meaning that certain effects have been found associated with given levels of exposure. Establishment of the more rigorous "causal"

relationship requires the inducement of direct or indirect evidence of causation. Evidentiary characteristics of a causal relationship include strength, specificity, and consistency.

The measures of exposure and effects are characterized by a unit of measurement, a specific pollutant, a given effect, an instant or interval of time, a geographic location, and a target population. The results of dose-effect studies are reported in terms of some combinations of the various levels of aggregation of these parameters.

Errors in representing dose-effect functions may be characterized as errors of specification and measurement. A particularly common and grave error of specification is committed in attempting to extrapolate a complete functional relationship from a few data points. Errors of measurement may be incurred in the course of measuring ambient levels, exposure, and effects. They may be represented graphically as an envelope about the plot of the dose-effect function. Such envelopes may be derived through replication of a specific investigation using new data, manipulation of values of the more important variables, combining results of several studies, applying "best" and "worst" case assumptions, and bounding available data points.

D. ANALYSIS OF SELECTED FUNCTIONS

This section provides an in-depth analysis of selected dose-effect functions to determine improvement in their validity and applicability. The presentation begins with selection of three functions and continues with an analysis based on the methodology discussed in the preceding section.

1. Selection of Functions

The impact of a dose-effect function on potential policy decisions may be determined on the basis of importance of the effect, data quantity and compatibility, data quality, and validity of the function. The relative importance of these criteria to the selection process depends on the category of effects, specific objectives of the selection process, and the subjective considerations of the investigator.

In light of all these considerations, the following three dose-effect functions were selected for in-depth analysis:

- Sulfur dioxide (or sulfates) - human mortality
- Ozone - injury to tobacco leaves
- Sulfur dioxide (or sulfates) - corrosion of zinc.

2. Effect of Sulfur Dioxide on Human Mortality

Effects of sulfur dioxide on human mortality represent the most intensively studied area of air pollution effects. The specific dose-effect function selected here, was developed by Buechley, et al. as a significant predictor of daily mortality in a large, densely populated, highly polluted metropolitan area (the New York-New Jersey-Connecticut air quality control region).

Measurements of air quality for the entire area were based on readings from only one air pollution monitoring station. The specific measure of concentration was obtained by averaging hourly concentration

readings over each 24-hour period. The target population was the entire population of the area and the measure of effect was total mortality. The study emphasized acute, rather than chronic effects by looking at daily averages and failed to take into account individual differences in susceptibility among the various classes of population.

Multiple regression analysis was used to estimate the individual contributions of a number of variables to the mortality ratio. These included an annual cycle, extreme heat, influenza epidemics, warm and cold weather, holidays, day of the week, sulfur dioxide, and coefficient of haze. With the other covariates controlled, sulfur dioxide and coefficient of haze showed a significant correlation with the mortality. However, it is likely that these measures had acted as proxies for sulfates or some other species. This restricts the applicability of the dose-effect function to other locations, where distribution of pollutants may differ significantly.

The recommended actions are: more extensive monitoring of SO_2 , sulfate, and particulate levels, collection of cause-specific mortality data, more detailed determinations of health effects of specific pollutants, and characterization of the target population.

3. Effects of Oxidants on Tobacco Leaves

Several investigators have characterized injury to tobacco leaves by oxidants and related factors. The specific dose-effect function selected here was developed by Heck, et al. for the Bel W-3 cultivar of tobacco. The graph of the function provides a vivid demonstration of the different effects of the concentration and time elements of exposure on leaf injury, permitting the interpretation of both chronic and acute effects.

The plants were grown in controlled environment chambers approximating field conditions. Ozone levels were measured with a coulometric MAST recorder.

Leaf injury was manifested in the form of flecs, which make the leaf undesirable as cigar wrapper, and measured in terms of the fraction of leaf surface covered by the flecs. Other measures that have been suggested include reduction of leaf growth rate, photosynthesis, or stomatal conductance.

Validity of the specific dose-effect function presented should be rather good, because it is based on results of controlled experiments. The principal reservations are the uncertain relationship between ozone measurements and oxidant concentration, failure to isolate the effect of meteorological factors, artificial flattening of concentration fluctuations, and subjective measurement of damage. The function suggests that exposure of the more sensitive varieties of tobacco to levels permitted under the national air quality standard for photochemical oxidants may cause substantial damage.

The recommended actions are: establishment of guidelines and criteria for conducting research on affects of air pollutants on vegetation, collection of more complete data on oxidant levels in rural areas, development of more precise and appropriate damage measurement techniques, and definition of the synergistic effects of pollutants.

4. Effect of Sulfur Dioxide on Corrosion of Zinc

The dose-effect function selected was developed by Haynie and Upham from results of a series of controlled experiments in eight series over a period of up to 64 months. It expresses a linear relationship between an atmospheric factor composed of SO_2 concentration and relative humidity on one hand, and corrosion rate of zinc, on the other. The authors conclude that SO_2 is a major cause of zinc corrosion and that a relative humidity in excess of 49 percent is required before SO_2 attack can become effective.

Panels of high-grade zinc sheet were exposed to ambient air for five different periods of time. SO_2 ambient concentration data were obtained from nearby monitoring stations. Extent of corrosion was measured by cleaning the panels to remove corrosion products and determining the weight loss.

The analytical relationship developed accounts for 92 percent of the variability of average corrosion rates and yields an r value of 0.96. The general range of the data spans both the national standard and prevalent ambient values, permitting interpolation of most data of value. The major errors are associated with SO_2 measurement and relationships between dose values and ambient levels at the exposure sites.

The only actions recommended are characterization of errors in measurement of SO_2 levels and performance of a less extensive series of tests on zinc-coated steel in parallel with zinc sheet to determine relative corrosion rates.

E. RESEARCH NEEDS

This final section delineates a limited number of suggestions for additional research that were culled from the material presented in the preceding sections. These suggestions pertain exclusively to development of dose-effect functions and do not deal with such other related and interesting topics as improvement in air quality monitoring and modeling techniques or better understanding of effect mechanisms. Successive subsections address methodological improvements in determination of exposure and effect and additional dose-effect studies.

1. Determination of Exposure

The following research needs are suggested:

- Determine how well air quality measurements at the monitoring station represent the ambient quality in the surrounding community
- Determine the impact of mobility and shielding of the subjects on their exposure
- Develop a composite index of exposure
- Explore the possibility of translating different measures of exposure
- Define current air quality monitoring requirements for potential future dose-effect studies.

2. Determination of Effect

The following research needs are suggested in this area:

- Assess and improve the accuracy and reliability of the various methods for determining morbidity in dose-effect studies
- Develop a method for determining changes in life expectancy due to exposure to air pollutants
- Provide uniform guidance for designing studies of the effects of air pollutants on vegetation.

3. Study Design

Recommended research projects in the area of study design are:

- Assess the relative cost-effectiveness of Lave's "dream study" and a corresponding conventional epidemiological study
- Prepare a manual for developing dose-effect functions.

4. Additional Dose-Effect Studies

The following additional dose-effect studies are recommended:

- Specific effects of NO₂ and nitrates
- Specific effects of different types of sulfates
- Chronic effects of low-level exposures to various pollutants
- Carcinogenic, teratogenic, and mutagenic effects of air pollutants
- Effect of oxidants on yields of major crops
- Synergistic effects of sulfur oxide and oxidants
- Long-term effect of pollutants on ecological balance
- Effects on paints, cement, rubber, plastics, and wood
- Effects on aesthetic appreciation of an area, including visibility
- Effects on climate and local weather conditions.

CHAPTER I. INTRODUCTION

This chapter introduces the major concepts and issues underlying the subject matter of this study. The topics covered include the role and nature of dose-effect functions, nature and effects of air pollutants, and the purpose, objectives, scope, and organization of the study report.

A. OVERVIEW

Dose-effect, or damage functions constitute an important link in the cycle between environmental pollution, resultant damages, and pollution control measures. This section explores the role and characteristics of these functions, as well as the nature and effects of the pollutants investigated.

1. Environmental Damages and Benefits

Nearly everyone is now convinced that there exists a causal relationship between environmental pollution levels and certain damages suffered by society. These may take the form of increased mortality, increased incidence and prevalence of disease, diminished enjoyment of the outdoors, reduced crop yields, more frequent maintenance and replacement of exposed materials, and other, less well-identified losses. This being the case, a reduction in pollution levels would bring about a corresponding decrease in these damages and produce a set of benefits equivalent to the difference in damages before and after the reduction took place. If the damages are reduced to the point at which they are no longer observed, then the benefits realized are equal to observed damages.

Legislators, planning officials, and other environmental decision makers are frequently faced with the decision of how much to reduce pollutant levels in the light of the associated direct costs of pollution control and possible secondary economic effects. In the past, these decisions were rather obvious and they were made in response to popular sentiment. However, with the passing of time, these costs became more acutely felt, especially in the wake of the energy crisis, while the beneficial effects of reduced, or at least stable, pollution levels were neither obvious nor easily measured. Clearly, the decision

makers would need a more sensitive tool for comparing and trading off the costs and benefits of various levels and types of pollution control. It was this need that gave birth to the science of environmental benefit/cost analysis.

Admittedly, benefit/cost analysis is not an exact science, primarily because social benefits and costs are diffuse and frequently difficult to express in monetary terms. Even so, the process of logical and systematic scrutiny inherent in benefit/cost analysis can contribute substantially to the ability of decision makers to improve the social welfare through more efficient allocation of the limited resources of the public treasury.

This potential contribution was recognized by the framers of the National Environmental Policy Act of 1969 (PL 91-190), primarily in Sections 102 and 204. Section 102 calls for the "identification and development of methods and procedures which will ensure that presently unquantified environmental amenities and values may be given appropriate consideration in decision making, along with economic and technical considerations." Section 204 charges the Council on Environmental Quality to gather, analyze, and interpret timely and authoritative information concerning the conditions and trends in the quality of the environment.

2. Nature of Damage Functions

There exists an interactive relationship among pollutant emissions, ambient air quality, damages and benefits, and policy decisions. This is illustrated in the diagram in Figure 1, where rectangles indicate processes and actions, and ellipses represent their products. The pollutants emitted by stacks, automobile exhaust pipes, and other sources undergo physical and chemical interaction in the atmosphere under the influence of meteorological factors to yield prevailing ambient pollutant levels. The resulting physical or biological damages are converted into some realistic economic terms and traded off against the costs of controls to guide decision makers on the extent and type of controls to be applied. Alternatively, economic damages can be determined directly as a function of ambient levels through surveys of property values, declared willingness to pay, legislative decisions, and litigation awards.

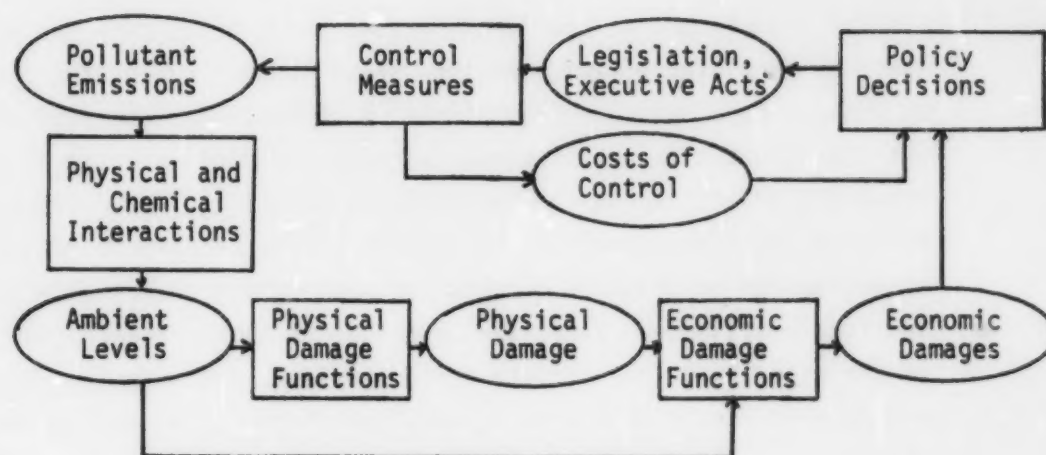


Figure 1. Cyclic Relationship Among Pollution-Related Activities and Their Products

A damage function represents the crucial link between ambient pollution levels and the resultant physical, biological, and/or economic damages. More specifically, a damage function is the quantitative expression of a relationship between exposure to specific pollutants and the type and extent of the associated damage to a target population. Exposure is typically measured in terms of ambient concentration levels and their duration and it may be expressed as "dosage" or "dose". Dosage is the integral of the time and ambient concentration to which the subject has been exposed, while dose represents that portion of the dosage that has been instrumental in producing the observed damage (e.g., the amount of pollutants actually inhaled in the case of health effects of air pollution).

The damage can become manifest in a number of ways and can be expressed in either physical and biological, or economic terms. If the effect is physical or biological, the resultant relationship is known as a physical or biological damage function, or a dose-effect function. In an economic damage function, on the other hand, the effect is expressed in monetary terms. Economic damage functions can be developed by assigning dollar values to the effects of a physical or biological damage function, or by direct correlation of economic damages with ambient pollutant levels.

In reporting a damage function, one needs to specify the pollutant, the dose rate, the effect, and the target population, or the "population at risk". Dose rate, or the rate at which ambient concentration varies with time, has a major influence on the nature and severity of the resultant effect. Long-term exposure to relatively low concentrations of air pollutants may result in manifestations of chronic disease, characterized by extended duration of development, delayed detection, and long prevalence. Short-term exposure to high concentration levels, on the other hand, may produce acute symptoms, characterized by quick response and ready detection, as well as chronic, cumulative, or delayed effects.

Specification of the population at risk involves the characterization of the nature and magnitude of the exposed population. It is crucial to this exercise for several reasons. First, it serves to define the total damages produced by a given level of exposure by multiplying the corresponding unit damage (e.g., increased mortality) for the specified population at risk (e.g., white males over 65) by the total number of units within this population. Secondly, it permits investigators to adjust their results to reflect the influence of various intrinsic (e.g., age, race, sex) and extrinsic (e.g., general health, occupation, income and education) variables in assessing the specific effects of air pollutants (e.g., increased incidence of lung cancer). Finally, it can provide useful guidance for allocating air pollution control resources by identifying areas with particularly susceptible populations exposed to relatively hazardous levels of pollutants.

A typical sigmoid, or S-shaped damage function, showing the damage corresponding to a given exposure to a specific air pollutant, is presented in Figure 2. The ordinate may represent either the number of individuals affected or severity of effect. The abscissa indicates the dosage in terms of time at a given ambient concentration, or in terms of ambient concentration for a fixed period of time. The lower portion of the curve suggests that, up to a certain exposure value, known as a threshold level, no damage is observed, while the upper portion indicates that there exists a damage saturation level (e.g., death of the target population or total destruction of the crops), beyond which increased

exposure levels do not produce additional damage. The middle, quasi-linear portion is very useful in that any data points here can be readily interpolated, and the frequent assumption about linearity of a damage function is most valid in this sector.

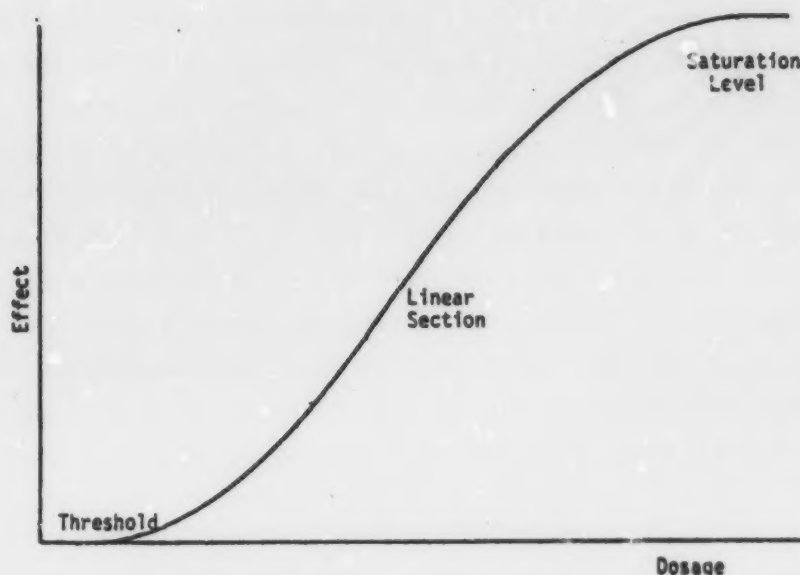


Figure 2. Hypothetical Dose-Effect Function

3. Development of Dose-Effect Functions

The data required to develop physical or biological damage functions are obtained primarily through epidemiological, field, clinical, toxicological, or laboratory investigations. The first approach involves the comparative examination of the effects of pollutants on selected segments of population exposed to different levels of pollution, in order to deduce the nature and magnitude of the likely effect. Field observations represent a similar approach to assessment of effects on animals, vegetation, and materials, and they are characterized by similar analytical techniques and concerns. Clinical studies are based on hospital observation of the results of exposure on human subjects. Toxicological investigations involve deliberate administration of controlled doses of pollutants to animal, and occasionally, human subjects, and observation of the resulting effects. Laboratory studies represent essentially the same approach for determining effects of pollutants on plants and materials.

The three principal techniques for analyzing the relationship between exposure and effect indices in epidemiological and field studies to construct a damage function are known as cross tabulation, multivariate regression, and non-parametric or distribution-free analysis. Cross tabulation is the simplest of the three. Multivariate regression provides a rapid indication of the degree of association between a large number of independent and the dependent variables and is readily programmable for computer operation. However, its validity is heavily contingent on a fairly precise a priori definition of the relationship between each independent and the dependent variables and on precise measurement of the independent variables. Thus, this technique is especially vulnerable to the poor precision in measurement and reporting of air pollution levels for a given segment of population. Non-parametric analysis, on the other hand, is free of these assumptions, but requires laborious data reduction for each of the many pairs of independent and dependent variables and expert judgment to guide each step of the process.

In the development of dose-effect functions on the basis of epidemiological or field studies, it is important to isolate or control the influence of cofactors and covariates. The former may be defined as factors that act in concert with the independent variables (e.g., relative humidity or cigarette smoking and pollutant level). Covariates, on the other hand, may be thought of as factors that vary jointly with the principal variable. The distinction between cofactors and covariates is not well defined, nor terribly useful or important. Their interference with results of the analysis can be reduced by holding them constant or with the aid of statistical techniques. When this cannot be done, it is frequently assumed that the distribution of these factors in the target population is sufficiently uniform to avoid vitiating the basic conclusions.

Finally, it should be noted that epidemiological and field studies and observations can only indicate an association between exposure to pollution and the observed effect, suggesting the existence of a causative relationship. Such a relationship can then be tested by toxicological and laboratory studies, or rendered plausible by the presentation of a plausible connective mechanism, or other weight of reason.

4. Merits and Drawbacks

As was noted earlier, dose-effect functions constitute an important link in the interactive relationship between pollutant emissions, resultant damages, and pollution control measures. Accordingly, they can serve as valuable instruments in reaching the following intermediate objectives in our social decision-making process:

- Popular conceptualization of the threats posed by environmental pollution and the beneficial changes wrought by abatement
- Determination of an optimal extent of pollution abatement through a cost-benefit tradeoff analysis
- Development of a more rational allocation of limited resources in improving environmental quality and other aspects of public welfare.

Despite these unquestioned conceptual merits, the development and application of dose-effect functions has been subjected to a great deal of critical commentary, much of it justified. The more cogent of these comments are listed below:

- Dose-effect functions are frequently based on insufficient data, requiring daring extrapolations of a curvilinear function from too few data points
- They attempt to represent complex and dynamic relationships by quasi-linear and static functions
- They force a quantitative interpretation on certain relationships that cannot be validly quantified
- They fail to account properly for synergistic or antagonistic relationships.

In fact, development of air pollution dose-effect functions is beset by a number of major difficulties that compromise their accuracy and reliability. Some of these difficulties can be readily overcome with the aid of available ancillary information, while others require the expenditure of much additional effort. The more important problem areas may be listed as follows:

- Collection and retrieval of reliable ambient air quality data
- Selection of exposure indicators
- Selection of representative populations
- Determination of effects
- Establishment of causal relationships
- Presentation of results.

Currently available air quality data do not represent well average ambient concentrations, and seldom reflect hourly, or even diurnal variations. Generation of more reliable and complete data would require a drastic expansion of current monitoring networks and a commitment to massive data handling or the development and application of substantially improved computer models for simulating atmospheric processes. Then there is the problem of selecting the proper exposure indicator for each pollutant, in terms of level, duration, and presence of other pollutants, or cofactors.

Another problem is the need to select sample populations that are representative of the population at large in terms of susceptibility to detectable levels of damage. In the case of health effects, this involves selection based on demographic and socio-economic makeup of the population at risk. Determination of effects involves choice of a useful effect indicator and differentiation from similar effects due to other factors. Perhaps the most formidable problem lies in identifying and documenting a plausible causal relationship, or at least a strong association between exposure to a given dose and observation of a specific effect and in deriving the corresponding damage function. Unfortunately, many damage functions are based on only a few discrete points, and require heroic assumptions about their shape.

All of these problems and others deserve much attention, because of the vast potential benefits to be derived from their solution. The state of the art of developing dose-effect functions, additional benefits to be extracted from current state of knowledge, and the more urgent problems to be addressed in the near future need to be explored in some depth. This is what this study hopes to accomplish.

B. PURPOSE AND SCOPE

This section delineates the general purpose, specific objectives, scope, and organization of this study, within the setting laid down in the preceding section.

1. Purpose and Scope

The purpose of this effort is to assess and demonstrate the utility and potential applications of existing and emerging physical air pollution damage (dose-effect) functions. The specific objectives designed to carry out this purpose are as follows:

- To assess the state of the art in developing air pollution dose-effect functions
- To interpret and communicate the significance of available and emerging damage functions
- To suggest improvements in analytical methodology and define new areas for study in furtherance of these objectives.

The effort was organized under five tasks presented in four chapters and an appendix, as set forth below:

- Prepare survey of literature on dose-effect functions (Chapter II)
- Prepare demonstration for the CEQ Annual Report (Appendix)
- Analyze selected dose-effect functions (Chapter IV)
- Prepare survey of methodology (Chapter III)
- Discuss future needs and projects (Chapter V).

The literature survey describes and evaluates the present state of knowledge regarding the development and uses of damage functions and provides the basis for selecting several damage functions for subsequent in-depth analysis. The brief demonstration for the CEQ Annual Report is

designed to show how air pollution damage functions can serve as interpretive aids in communicating the significance of air quality trends to persons who lack technical training. The analysis of selected dose-effect functions is designed to enhance the scientific validity and usefulness of these functions. The methodology survey describes and evaluates the various analytical approaches and techniques used in the interpretation of data and in the construction and application of air pollution damage functions. Finally, the last task addresses the more important needs for further study, research, data collection, and other development.

The scope of this effort can be defined in terms of pollutants, effects, and effect categories. These items are spelled out in Table 1 for air pollutants and discussed briefly below. Water pollutants are considered only in those selected cases where a significant damage function has been developed. Only physical and biological, as distinct from economic, effects are examined and both chronic and acute responses are considered. The effect categories encompass health effects, damage to vegetation, damage to materials, and other effects, such as visual impairment or climatic changes.

2. Pollutants Studied

The air pollutants included in this study are identified in Table 1. The term "particulates" refers to a wide variety of solid and liquid airborne particles introduced by a number of human and natural activities. The effects of certain specific particulates, such as sulfates, nitrates, and fluorides, are covered elsewhere, but even inert particles tend to aggravate the effect of gaseous pollutants. Particulates are also responsible for the soiling of building materials and other exposed surfaces, as well as impaired visibility.

Sulfur dioxide is formed by oxidation of sulfur, primarily during combustion of sulfur-bearing substances, such as coal or oil, but also in industrial processes. In combination with particulates, moisture, and/or oxidants, it forms acid sulfates which are very damaging to human health, vegetation, and materials. Health effects associated with sulfur

Table 1. Characteristics and Effects of Major Air Pollutants

Pollutant	Characteristics	Principal Sources	Health Effects	User Effects
Total Suspended Particulates* (dust, pollen, etc., soil, metals)	Any liquid or solid matter dispersed in the atmosphere	Natural processes (e.g., volcanic eruptions, wind erosion, forest fires, atmospheric reactions); stationary combustion (especially of solid fuels); construction activities; industrial processes	Some direct effects, but primarily aggravation of the effects of gaseous pollutants	Interference with photosynthesis of plants. Soiling and deterioration of building materials, electric contacts, and other exposed surfaces. Impaired visibility and insulation; cloud formation.
Sulfur Dioxide* (SO ₂)	A colorless gas with pungent odor	Combustion of sulfur-containing fuels; smelting of sulfur-bearing metal ores; industrial processes; natural processes (e.g., volcanic eruptions, atmospheric reactions)	Aggravation of respiratory diseases, including asthma, chronic bronchitis, emphysema; reduced lung function; irritation of eyes and respiratory tract; suspected contribution to respiratory and gastro-intestinal neoplasms	Leaf injury and reduced growth in plants. Corrosion of metal; deterioration of paper, textiles, leather finishes and coatings, building stone. Formation of acid rain, impaired visibility.
Nitrogen Dioxide* (NO ₂)	A brownish-red gas with pungent odor	Motor vehicle exhaust; high temperature combustion; atmospheric reactions	Aggravation of respiratory diseases; suspected contribution to cardiovascular disease, respiratory neoplasms, and chronic nephritis; suspected increase in susceptibility to infection	Reduced growth and premature leaf drop in plants. Fading of dyes. Disruption of atmospheric ozone layer; impaired visibility.
Photochemical Oxidants* (O ₃ , PAN, aldehydes, other)	Colorless gaseous compounds; powerful oxidizing agents; principal components of photochemical smog	Atmospheric reactions	Aggravation of respiratory and cardiovascular diseases; reduced lung function; irritation of eyes and respiratory tract; suspected contribution to respiratory neoplasms and impaired fetal development	Leaf injury, reduced growth, and premature leaf and fruit drop in plants. Deterioration of rubber products; fading of dyes. Impaired visibility.
Carbon Monoxide* (CO)	A colorless, odorless, tasteless gas; has high affinity for hemoglobin in the blood	Motor vehicle exhaust; incomplete combustion of carbonaceous substances; natural processes (e.g., forest fires, decomposition of organic matter)	Reduced tolerance for exercise; impaired mental activity; impaired fetal development; aggravation of cardiovascular diseases	Not known.
Hydrocarbons* (HC)	Compounds of hydrogen and carbon in gaseous (e.g., methane, ethylene, acetylene) or particulate (benzo-a-pyrene) form	Motor vehicle exhaust; incomplete combustion of carbonaceous substances; processing, distribution, and use of petroleum compounds; natural processes (e.g., forest fires, metabolic processes of plants, atmospheric reactions)	Suspected contribution to neoplasms by benzo-a-pyrene	Major ingredient in the formation of oxidants through atmospheric reactions.
Sulfates (SO ₄)	Corrosive aerosol in the form of sulfuric acid (H ₂ SO ₄) mist or rain	Oxidation of sulfur dioxide in the atmosphere in the presence of moisture	See sulfur dioxide	See sulfur dioxide for plants. Damage to electric contacts. Acidification of soil and surface waters.
Nitrates (NO ₃)	Corrosive aerosol in the form of nitric acid (HNO ₃) mist or rain	Oxidation of nitrogen dioxide in the atmosphere in the presence of moisture	See nitrogen dioxide	See nitrogen dioxide for plants and materials. Acidification of soil and surface waters.
Fluorides (F ⁻)	Gaseous and solid compounds of fluorine	Industrial processes (e.g., production of phosphate fertilizer, aluminum metal, brick, and tile); combustion of coal	Irritation of respiratory tract and other sensitive tissues; inhibition of enzyme action	Leaf injury and reduced growth in plants. Corrosion of metals, damage to ceramics. Deposition in soil and accumulation in crops.

(*) Pollutants for which national environmental standards have been promulgated

oxides include aggravation of respiratory diseases, such as asthma, chronic bronchitis, and emphysema, reduced lung function, irritation of eyes and respiratory tract, and suspected contribution to respiratory and gastrointestinal neoplasms. Vegetation suffers from leaf injury and reduced growth. Materials effects take the form of corrosion of metals, deterioration of textiles, paper, leather, finishes and coatings, and building stone.

Nitric oxide (NO) and some nitrogen dioxide (NO₂) is formed by reaction of oxygen and nitrogen during high temperature combustion, such as occurs in automobile engines. Nitric oxide reacts with oxygen in the atmosphere, especially in the presence of photochemical oxidants, to form nitrogen dioxide, which then undergoes additional complex reactions with ozone and hydrocarbons under the influence of UV radiation to produce the familiar smog. Nitrogen dioxide is an acute irritant responsible for a number of health effects, such as aggravation of respiratory diseases and suspected contribution to cardiovascular diseases, respiratory neoplasm, and chronic nephritis. It has been also implicated in reduced growth and premature leaf drop of plants and in the fading of dyes. Investigations of the effect of nitrogen dioxide has been greatly handicapped by its numerous atmospheric reactions, the resultant rapid fluctuation of its ambient concentration, and the lack of an acceptable measurement technique.

Photochemical oxidants, referred to incorrectly as smog, are formed by a series of complex atmospheric reactions from hydrocarbons and the nitrogen oxides. Their chief constituents are ozone (O₃) and peroxyacetyl nitrate (PAN), as well as a number of other organic compounds. Oxidants have been held responsible for aggravation of respiratory and cardiovascular diseases, reduced lung function, irritation of eyes and respiratory tract, and suspected contribution to respiratory neoplasm and impaired fetal development. Effects on vegetation and materials include leaf injury, reduced plant growth, premature leaf and fruit drop, deterioration of rubber and textile products, and fading of paints and dyes.

Carbon monoxide and hydrocarbons are formed by the incomplete combustion of organic fuels, such as occurs in automobile engines. Carbon monoxide has been implicated in reduced tolerance for exercise, impaired mental activity, impaired fetal development, and aggravation of cardiovascular diseases. The major impact of hydrocarbons lies in the formation of photochemical oxidants.

Acid rain is formed by scavenging of sulfuric and nitric acid mist by raindrops. The effects of acid rain on plants and materials resemble those of sulfur oxides. In addition, acid rain contributes to the acidification of surface waters and soil, which is detrimental to plant growth and to various uses of water.

Fluorides are formed by source industrial processes, including the production of aluminum, steel, ceramics, and phosphate fertilizer, and therefore, they represent a localized pollution problem. Although the health and material effects of fluorides have not been adequately investigated, these compounds are known to produce foliar injury and reduced growth in plants. They can also affect adversely animals foraging on these plants.

II. SURVEY OF STATE OF KNOWLEDGE

The effects of air pollutants have been addressed by numerous investigators during the past decade. However, many of these studies display limited applicability, insufficient concern for impact of covariates, or other flaws that frustrate aggregation of their results into a valid and meaningful dose-effect function. A number of selected studies are surveyed here for five categories of effects: human health, vegetation, materials, aesthetics and weather, and effects of water pollutants.

A. EFFECTS ON HUMAN HEALTH

Effects of air pollutants on human health have received the most attention because of their relatively high social importance. Studies of these effects are reviewed here for each of the major pollutants: sulfur oxides and particulates, nitrogen oxides, photochemical oxidants, carbon monoxide, and non-specific air pollution.

1. General Remarks

The most generally useful relationships between exposure to air pollutants and health effects have been obtained from epidemiological studies, which compare observed effects on selected target populations with exposure as a function of location or time. Clinical and toxicological observations, based on controlled experience with human and animal subjects, have been excluded, because of the difficulty of extrapolating their results to the general human population. Studies that do not formulate meaningful quantitative relationships, fail to control for relevant covariates, or merely report on catastrophic air pollution episodes have also been excluded here, because they do not contribute substantially to the development of dose-effect functions. Nevertheless, inclusion or exclusion of a specific investigation in this listing is not necessarily a reflection on the quality of work or validity of the results.

A summary listing of the investigations reviewed here is provided in Table 2, which specifies the pollutant, major covariates, target population, effects, and author reference. The major pollutants

Table 2. Selected Studies of Health Effects of Major Air Pollutants

Pollutants	Target Population	Covariates	Results	Reference
Particulates, sulfates	U.S. SMSAs	Population, population density, age, race, income	A 10-percent reduction in minimum biweekly sulfate and mean biweekly particulates associated with 0.91-percent reduction in mortality	Lave and Seskin, 1973
Sulfur dioxide	Chicago, Denver, Philadelphia, St. Louis, Washington, D.C.	Weather, day of the week	A decrease of 0.092 ppm in the mean concentration of sulfur dioxide associated with a decrease of 63 deaths per day (Chicago)	Lave and Seskin, in press
Sulfur dioxide	U.S. SMSAs	Temperature, precipitation, humidity, age, race, six socioeconomic factors	Sulfur dioxide found significant in explaining mortality rates	McDonald and Schwing, 1973
Sulfates	U.S. SMSAs; male, white, over 65	Various climatic, demographic, and socioeconomic factors	Found significant association between sulfates and mortality from arteriosclerotic heart disease and cancer of respiratory and gastrointestinal tract	Sprey and Takacs, 1973
Particulates, sulfur dioxide	New York City	Weather	Found significant association between sulfur dioxide and particulate levels and mortality from respiratory and heart disease	Hodgson, 1970
Smoke shade, sulfur dioxide	New York City	Weather	Found association of daily mortality with sulfur dioxide stronger than with any weather variable	Glasser and Greenburg, 1971
Smoke shade,	New York City	Weather, day of the week	Between 18.12-36.76 excess deaths per day associated with air pollution; 80 percent of effect ascribed to smoke shade, 20 percent to sulfur dioxide	Schimmel and Greenburg, 1971
Sulfur dioxide	New York Metropolitan region	Temperature, epidemics, disasters, holidays, day of the week, time trends	Found association between sulfur dioxide levels and residual mortality	Buechley <i>et al.</i> , 1973
Particulates	Buffalo, N.Y.	Age, sex, race, income	Mortality from chronic respiratory disease found twice as high at high as at low particulate levels	Winkelstein <i>et al.</i> , 1967
Particulates	Buffalo, N.Y.	Age, sex, race,	Mortality from gastric and prostatic cancer found twice as high at high as at low particulate levels	Winkelstein and Kantor, 1969a, 1969b
Particulates	Buffalo, N.Y.	Age, sex, race, income	Found association between particulate levels and mortality from arteriosclerotic heart disease, cerebrovascular disease, and cirrhosis of the liver	Winkelstein and Gay, 1971
Particulates, soiling, dust, sulfur dioxide, sulfation	Nashville, Tenn.	Age, sex, race, income	Found association between soiling and sulfur dioxide and total morbidity and cardiovascular disease morbidity; association between sulfation, dustfall, and particulates and cardiovascular disease in females	Zeidberg <i>et al.</i> , 1964
Particulates, soiling, dust, sulfur dioxide, sulfation	Nashville, Tenn.	Age, sex, race, income	Found association between particulates and cardiovascular mortality in females; association between soiling and sulfation and mortality from respiratory disease but not lung cancer	Zeidberg <i>et al.</i> , 1967a, 1967b

Table 2 (continued)

Pollutants	Target Population	Covariates	Results	Reference
Particulates, soiling, dust, sulfur dioxide, sulfation	Nashville, Tenn.	Age, sex, race, income	Found association between pollutant levels and total cancer mortality and cancer of esophagus, stomach and bladder, but not lung cancer	Hagstrom <i>et al.</i> , 1967
Particulates, sulfur dioxide	Los Angeles	Weather	Found significant association between pollutant levels and disease-specific hospital admissions and lengths of stay	Sterling <i>et al.</i> , 1966, 1967, 1969
Soiling	Allegheny County (Pittsburgh)	Weather, day of the week	Doubling of soiling index associated with 22-percent increase in admissions for respiratory emergency	Silverman, 1973
Particulates, sulfation	Berlin, N.H. and Chilliwack, B.C.	Smoking	Found association between particulate and sulfation levels and incidence of chronic respiratory disease	Ferris and Anderson, 1962, 1964; Anderson <i>et al.</i> , 1965; Ferris <i>et al.</i> , 1973
Nitrogen dioxide	Chattanooga school children	Smoking, socio-economic	Rates of acute respiratory illness found higher in areas with high NO ₂ levels	Shy <i>et al.</i> , 1970a, 1970b, 1973
Nitrogen dioxide	Chattanooga school children	Years of exposure	Found association between exposure to NO ₂ and incidence of bronchitis	Pearlman <i>et al.</i> , 1971
Nitrogen dioxide	Parents of Chattanooga school children	Smoking, ages, sex, race	No association found between NO ₂ and chronic bronchitis	Chapman <i>et al.</i> , 1973
Nitrogen dioxide	U.S. SMSAs, white males and females over 65	Weather, socio-economic	Mortality from hypertensive heart disease increased by about 200 per 100,000; lung cancer increased by 50 percent for males, and 130 percent for females upon increasing NO ₂ levels from 0.03 to 0.08 ppm	Sprey and Takacs, 1973
Photochemical oxidants	School children in Los Angeles		Found no significant association between oxidant levels and school absenteeism due to respiratory illness	Wayne and Wehrle, 1969
Photochemical oxidants	Student nurses in Los Angeles	Nitrogen dioxide, carbon monoxide, temperature	Developed thresholds for several health symptoms	Hammer <i>et al.</i> , 1974
Carbon monoxide	Los Angeles County	Oxidants, temperature	Found significant association between daily mortality and carbon monoxide, but not oxidants	Hexter and Goldsmith, 1971
Carbon monoxide			Found association between carbon monoxide and angina and intermittent claudication	Aronow <i>et al.</i> , 1972, 1973, 1974
Non-specific air pollution	Students at 7 California universities	Climatic and socioeconomic variables, holidays, chronic conditions	Found association between air pollution and excess incidence of respiratory illness	Durnham, 1974
Benzo-a-pyrene	U.S. and 19 other countries		An increase of 1 µg/1000 m ³ in concentration of benzo-a-pyrene was associated with 5-percent increase in mortality from lung cancer	Carnow and Meier, 1973
Oxidants, nitrogen dioxide, carbon monoxide	California		Developed a series of dose-effect functions on the basis of expert opinions	Leung <i>et al.</i> , 1975

investigated are sulfur oxides and particulates, photochemical oxidants, carbon monoxide, and unspecified air pollutants. Sulfur oxides and particulates are considered jointly because of their strong synergistic effects on health. The actual causative agent is probably some combination of sulfur dioxide, acid sulfates, and other particulates.

A wide variety of health effects are explored in these investigations. The principal effects are mortality and morbidity (i.e., incidence and prevalence of disease), but each of these may be further characterized by various specific diseases and measured by a number of indicators. The diseases are respiratory and cardiovascular dysfunctions, neoplasms of the respiratory and gastrointestinal tracts, chronic nephritis, and impaired fetal development and mental function. The indicators of morbidity include work and school absenteeism, hospital admissions and residence days, doctors' visits, and personal histories.

2. Sulfur Oxides and Particulates

A number of important cross-sectional studies have compared the effects of sulfur oxides and particulates on populations of metropolitan areas. Lave and Seskin (in press) investigated the relationship between sulfate and particulate pollution and mortality rates in more than 100 SMSAs, using multivariate regression analysis and controlling for age, racial composition, population density, income, and geographic size of SMSA. The most significant pollution variables were the minimum biweekly sulfate and the mean biweekly particulate levels. Increase of $1 \mu\text{g}/\text{m}^3$ in the former (raising the mean from 4.72 to $5.72 \mu\text{g}/\text{m}^3$) was associated with an increase of 6.3 per 100,000 in the total death rate, whereas an increase of $10 \mu\text{g}/\text{m}^3$ in the latter (raising the mean from 118.1 to $128.1 \mu\text{g}/\text{m}^3$) was associated with an increase of 4.5 per 100,000 in the total death rate.

A significant relation between daily SO_2 levels and daily mortality in Chicago was found by Lave and Seskin (in press) in a study of SO_2 , NO , NO_2 , CO , and hydrocarbons in five cities (Chicago, Denver, Philadelphia, St. Louis, and Washington, D.C.). A regression including current and lagged values of SO_2 , three weather factors, and day of the week, associated a decrease of 50 percent in SO_2 level with a

decrease of 5.5 percent in daily deaths. A significant relation was also found for NO in Chicago. A study by Cannow *et al.* (1969) in Chicago showed a similar association between mortality from respiratory diseases and SO_2 levels, but an earlier study of the same variables by Burrows *et al.* (1968) found no such relation.

In another analysis of data from SMSAs, McDonald and Schwing (1973) employed a ridge regression analysis to investigate the association between air pollution potential and mortality rates, including a number of climatic and socioeconomic variables. The variable representing sulfur dioxide was quite significant in explaining variations in the mortality rate between SMSAs in spite of the ridge transformation. However, data for SO_2 , NO_x , and HC were deficient and the authors used "pollution potentials", based on pollutant emissions and weather factors, rather than ambient air concentrations. The relationship of these potentials to actual pollutant levels is not known, so that the results contribute only supportive evidence.

An application of nonparametric analysis to cause-specific mortality statistics for 42 SMSAs (Sprey *et al.*, 1973) revealed a positive correlation of mortality from arteriosclerotic heart disease and neoplasms of the respiratory and gastrointestinal tracts with sulfate levels. For white males over 65, an increase in median sulfate concentrations from $5 \mu\text{g}/\text{m}^3$ to $24 \mu\text{g}/\text{m}^3$ was associated with a 19 percent increase in mortality from arteriosclerotic heart disease (see Figure 3).

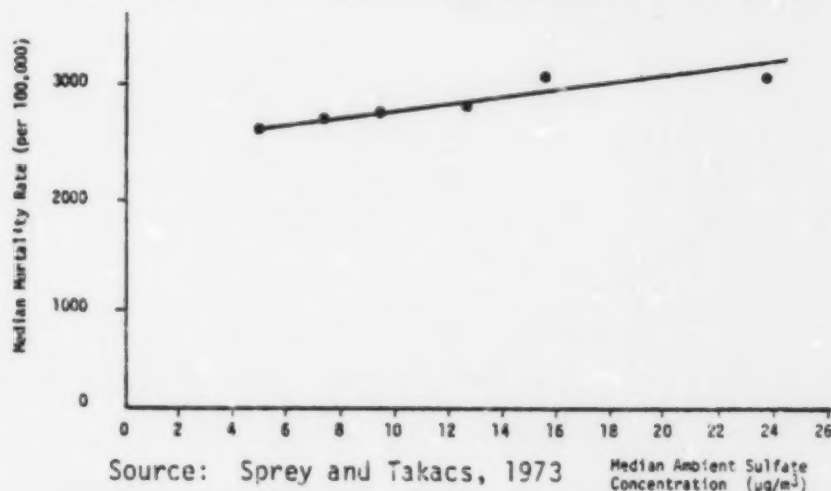
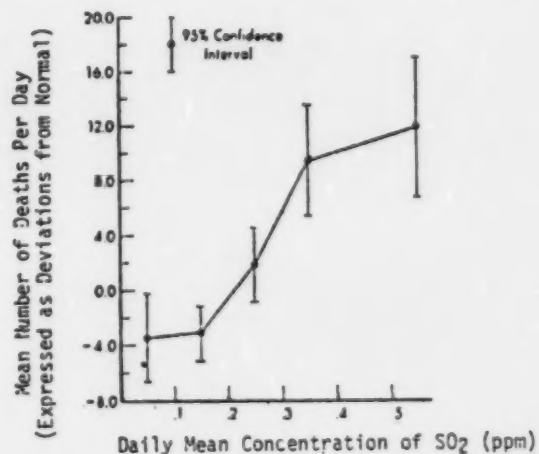


Figure 3. Relationship Between Median Ambient Sulfate Concentration and Median Mortality from Arteriosclerotic Heart Disease

A number of daily time series studies were made in New York City and its metropolitan area. A study of short-term effects by Hodgson (1970) used multiple regression to analyze the relationships among mortality, air pollution (particulates and sulfur dioxide), and several meteorological factors. Mortality from respiratory and heart diseases for all ages was found to be significantly related to the level of air pollution. However, any detailed analysis of the acute effects of pollution was frustrated by the employment of moving averages of the variables.

Glasser and Greenburg (1971) found a definite relationship between deviations from a five-year "normal" in New York City's daily mortality, and daily mean concentration of sulfur dioxide (see Figure 4). In a regression analysis including sulfur dioxide, rainfall, wind speed, sky cover, and temperature deviations as explanatory variables, the respective beta coefficients were 0.292, 0.024, 0.015, and 0.061. These coefficients were independent of measurement units and could form the basis for a dose-effect function. Glasser and Greenburg measured mortality in terms of deviations from a 15-day moving average. This measure is suggestive of cycles in the data and of lags in the effects of pollution, but lagged variables were never utilized and the investigation never questioned the timing of the effect.



Source: Glasser and Greenburg, 1971

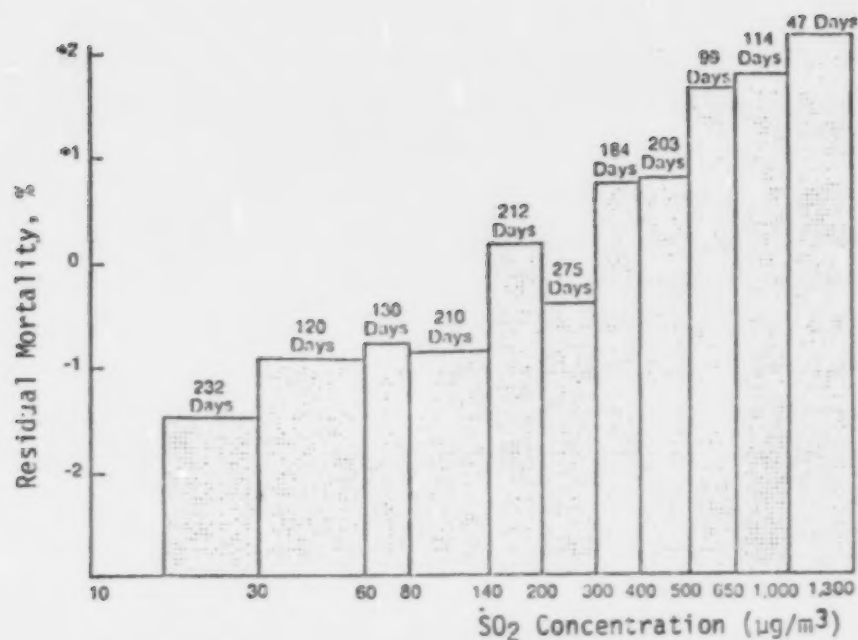
Figure 4. Relationship Between Mean Number of Deaths and Mean SO₂ Concentration in New York City

Schimmel and Greenburg (1972) performed a similar analysis for New York City. Using a linear model, they regressed daily mortality on sulfur dioxide and smoke shade levels for the same and previous days, while controlling for weather factors and day-of-the-week effects. They concluded that, if air pollution in New York City were reduced to zero, there would be, on the average, from 18.12 to 36.74 fewer deaths each day, depending on the particular pollution variate under consideration. This represents about 12 percent of the over half-million deaths occurring during the six-year study period. Furthermore, in looking at the individual effects of the two pollutants, they concluded that 80 percent of the excess deaths could be attributed to smoke shade, and only 20 percent to sulfur dioxide.

The method of analysis was novel and deserves comment. Instead of including measures of climate and other factors as independent variables in the regressions, Schimmel and Greenburg adjusted the air pollution variables to remove these effects. The adjustment was employed to eliminate spurious associations. However, in eliminating most of the variations in the air pollution variables, the technique results in biased estimates of the effects of air pollution on mortality. Any use of their findings for the construction of dose-effect functions must be made with this in mind.

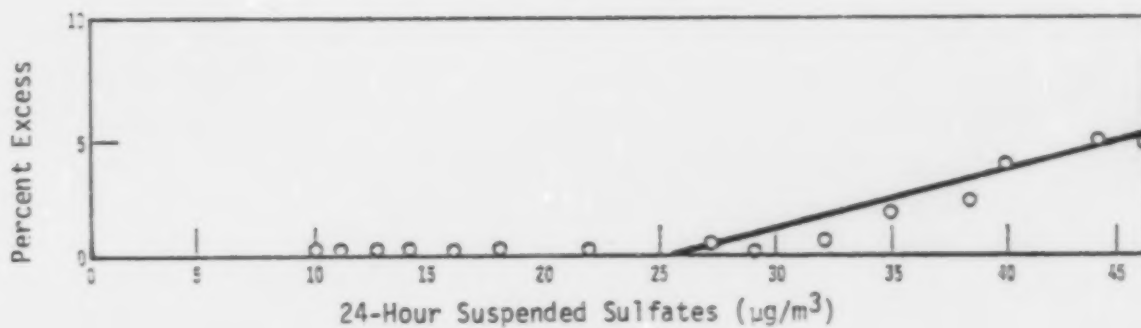
Buechley *et al.* (1973) used multiple regression to analyze the relationship between daily mortality and sulfur dioxide levels in the New York-New Jersey metropolitan region between 1962-1966. The analysis controlled for temperature, holidays, day of the week, and epidemics, and eliminated "disasters and time trends". Residual mortality values (observed minus predicted mortality) were found to follow a gradient with classes of SO_2 concentrations (see Figure 5). The effects of coefficient of haze (COH) were discussed, but no quantitative assessment was presented.

Schimmel and Murawski (1975) and Buechley (1975) have recently offered a re-evaluation of their New York City data. Both reach the conclusion that SO_2 was a proxy for some other factor and not the causal agent. Schimmel and Murawski state:



Source: Buechley et al., 1973

Figure 5. Relationship Between Classes of SO₂ Concentration and Mean Residual Mortality in New York City - New Jersey



Source: Adapted from Finklea et al., 1975

Figure 6. Relationship Between Sulfate Levels and Excess Mortality

"Our statistical studies, as well as those of Dr. Buechley, suggest that SO_2 is not only serving as an indicator of air quality but also that SO_2 is not an injurious pollutant, at least at the ambient levels encountered in New York City in the 1960's--namely, average levels of 0.2 ppm (525 Mg/m^3) and peak levels of 0.6 ppm (1575 Mg/m^3). This is entirely consistent with results of published data on the effects of SO_2 on humans and animals."

The results obtained by Schimmel and Greenburg (1972) and by Buechley et al. (1973) were combined by Finklea et al. (1975) in a form which recognized only excess mortality, at SO_2 levels above normal, and employed an empirical equation to convert SO_2 measurements into sulfate equivalents. The lower-than-average mortalities at low SO_2 levels which appear in both of the original publications were treated as zero excess mortality. The function is shown in Figure 6 and may be expressed by the equation:

$$\text{Percent excess mortality} = 0.25 \left(\frac{\text{sulfate concentration above } 25 \text{ } \mu\text{g/m}^3}{25 \text{ } \mu\text{g/m}^3} \right)$$

A series of studies in and around Buffalo, New York, by Winkelstein and colleagues focused on particulate pollution. The populations at risk were white males and females, 50-69 years old, and results were developed for five levels of family income. Effects studied were mortalities from chronic respiratory disease (asthma, bronchitis, emphysema), gastric cancer, prostatic cancer, arteriosclerotic heart disease, and cirrhosis of the liver. These studies offer a great deal of useful material for the development of damage functions. A majority of the sets, male and female, show an increase in mortality with rising pollution and income level. The studies are discussed below and the results are summarized in Table 3.

Winkelstein et al. (1968) performed a similar study using oxides of sulfur as the pollution measure. A positive association was found between sulfation and chronic respiratory disease mortality in the two lowest economic groups, the only ones with sufficient data. Winkelstein and Kantor (1969a, 1969b) found the rate of mortality from both gastric and prostatic cancer more than twice as high in polluted areas as in relatively clean ones. Winkelstein and Gay (1971) found a consistent

Table 3. Mortality Rates (per 100,000) At Several Pollution and Income Levels in Buffalo

Median Income \ Particulate Level in $\mu\text{g}/\text{m}^3/\text{day}$	Particulate Level in $\mu\text{g}/\text{m}^3/\text{day}$			
	< 80	80-100	100-135	> 135
I 3005-5007	- - 18 ^{c/} - -	126 0(0) 26 1572(366) 129(0)	a/ b/ 271 63(33) 38 1647(652) 129(37)	392 136(24) 39 1774(1029) 359(69)
II 5175-6004	136 45(8) - 191(388) 28(11)	154 41(18) - 1115(436) 82(19)	172 48(25) - 1234(534) 144(30)	199 84(40) - 1350(689) 173(47)
III 6013-6614	- - 18 ^{f/} - -	- 39(30) 23 1024(400) 48(17)	- 51(16) 33 1045(460) 87(25)	- 51(49) 51 1387(540) 81(57)
IV 6618-7347	70 15(5) - 820(345) 37(31)	80 38(21) - 1066(346) 33(21)	177 63(0) - 1149(493) 83(27)	- - - - -
V 7431-11792	79 26(14) - 789(290) 26(11)	109 16(9) - 1917(320) 17(17)	0 0(0) - 697(197) 95(0)	- - - - -

a/ Asthma, bronchitis, emphysema, white males, 50-69

b/ Gastric cancer, white males (females), 50-69

c/ Prostatic cancer, white males, 50-69, income levels I and II

d/ Arteriosclerotic heart disease, white males (females), 50-69

e/ Cirrhosis of the liver, white males (females), 50-69

f/ Prostatic cancer, white males, 50-69, income levels III, IV, and V

Source: Winkelstein et al., 1967, 1968; Winkelstein and Kantor, 1969a, b; Winkelstein and Gay, 1971

gradient for arteriosclerotic heart disease from the lowest to the highest pollution level, except in the highest economic class. Results were similar, though less consistent, for cerebrovascular disease. A graded positive association was found between suspended particulates and cirrhosis of the liver.

Zeidberg et al. (1964) found significant associations of total morbidity and cardiovascular disease morbidity with soiling index and sulfur dioxide in males in Nashville, Tennessee. Cardiovascular disease morbidity in females showed a direct relationship with sulfur dioxide, sulfation, soiling, dustfall, and suspended particulates (see Table 4). For cardiovascular mortality, a regular pattern was noted for females but not for males (Zeidberg et al., 1967). Zeidberg et al. (1967) found that total respiratory disease mortality in Nashville was directly related to sulfation and soiling, but death rates for other specific diseases followed no definite pattern, and socioeconomic differences could not explain the observed associations (see Table 5).

Hagstrom et al. (1967) found total cancer mortality to be generally higher in polluted than in relatively clean areas of Nashville, Tennessee (see Table 5). They also found significant mortality rate increases associated with cancer of the stomach, esophagus, and bladder. However, they were unable to isolate an air pollution effect on lung cancer mortality. These findings parallel the cancer observations in Buffalo.

Studies of hospital admissions in Los Angeles and a range of pollutant indices have shown that diseases rationally connected with air pollution do in fact show some correlations, especially with SO_2 and particulates, and NO_x and oxidants (Brant and Hill, 1964; Brant, 1965; Sterling et al., 1966, 1967, 1969). However, the results were not presented in a manner useful for the construction of dose-effect functions.

Using multivariate statistical analysis techniques, Silverman (1973) studied daily emergency admissions at hospitals in Allegheny County for treatment of respiratory diseases (particularly bronchitis and

Table 4. Mortality Rate (per 100,000) at Several Pollution Levels in Nashville

Pollution Indicator \ Pollution Level	Pollution Level		
	Low	Moderate	High
Sulfation ² ($\mu\text{g}/100\text{ cm}^2/\text{day}$)	≤ 0.150 126.3(160.0) ^{a/} 36.2(31.1) ^{b/}	0.151-0.350 114.9(134.2) 34.1(40.4)	≥ 0.351 192.0(168) 64.0(45.8)
Soiling (COHS)	≤ 0.330 95.6(126.7) 20.4(16.2)	0.331-0.830 122.4(138.9) 35.0(38.1)	≥ 0.831 140.3(157.8) 52.8(55.2)
Dustfall ($\text{T}/\text{mi.}^2/\text{mo}$)	≤ 5.00 84.8(123.7) 31.6(28.9)	5.01-15.00 135.0(146.4) 39.0(42.0)	≥ 15.01 116.7(150.0) 16.7(50.0)
Particulates ($\mu\text{g}/\text{m}^3/24\text{ hrs.}$)	≤ 100 139.4(123.7) 41.1(36.3)	101-199 107.9(127.0) 36.1(38.0)	≥ 200 130.4(176.4) 26.1(52.8)
Sulfur Dioxide ($\text{ppm}/24\text{ hrs.}$)	≤ 0.0050 80.6(115.8) 22.2(28.9)	0.0051-0.0100 116.9(135.6) 36.8(36.8)	≥ 0.0101 177.4(171.8) 47.2(51.8)

a/ All causes, white middle-class males (females), ≥ 55

b/ Cardiovascular disease, white middle-class males (females), ≥ 55

Source: Zeidberg *et al.*, 1964

pneumonia) and found that a doubling of the soiling index was associated with a 22 percent rise in admissions. The air pollution variable was also associated, to a much lesser degree, with emergency heart disease admissions, but not with emergency admissions for deliveries, appendectomies, and other problems. A similar study of demand on health services for diseases aggravated by air pollution was made by Jaksch (1973), who found an association with suspended particulate concentrations.

Table 5. Mortality Rate (per 100,000) at Several Pollution Levels in Nashville

Pollution Indicator \ Pollution Level	Pollution Level		
	Low	Moderate	High
Sulfation ₂ (mg/100 m ² /day)	<u>≤ 0.150</u> 71.59 144.66	<u>0.151-0.399</u> 76.59 128.92	<u>≥ 0.400</u> 125.19 ^{a/} 149.95 ^{b/}
Soiling (COHS)	<u>≤ 0.350</u> 67.31 123.75	<u>0.351-1.099</u> 75.22 129.99	<u>≥ 1.100</u> 119.00 152.59
Dustfall (T/mi. ² /mo.)	<u>≤ 5.00</u> 77.48 130.91	<u>5.01-11.99</u> 74.92 129.83	<u>≥ 12.00</u> 118.47 145.35
Sulfur Dioxide (ppm/24 hrs.)	<u>≤ 0.005</u> 99.54 138.40	<u>0.006-0.012</u> 71.29 129.06	<u>≥ 0.013</u> 117.74 140.70

^{a/} All respiratory disease, middle class, age-adjusted

^{b/} All cancer, middle class, age-adjusted

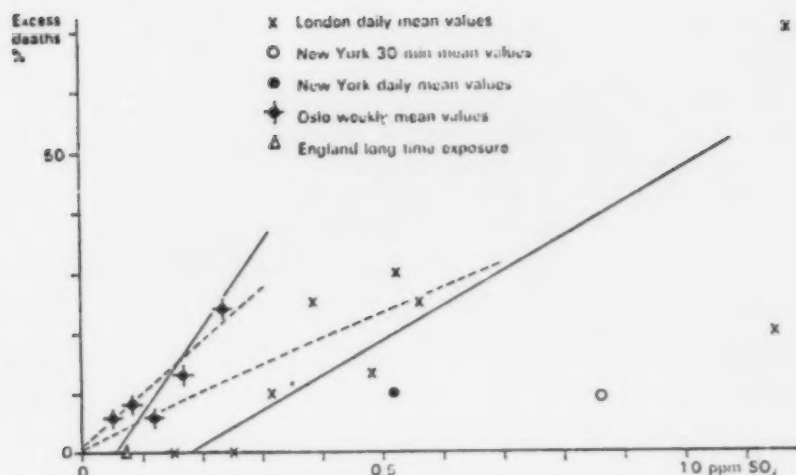
Source: Zeidberg et al., 1967; Hagstrom et al., 1967

A classic illustration of a cross-sectional epidemiologic study is the work of Ferris and Anderson in Berlin, New Hampshire, and Chilliwack, British Columbia (Ferris and Anderson, 1962, 1966; Anderson et al., 1965; Ferris et al., 1973). The incidence of chronic respiratory disease (bronchitis) and lung function were measured and smoking was controlled. A follow-up of the initial Berlin study for the period 1961-1967 found that a decrease of 30-40 percent in particulate level and sulfation yielded a reduction in chronic respiratory disease. Interpretation of these results should be tempered by awareness of the poor quality of the data and the likely socioeconomic differences between the two locations.

Goldberg et al. (1972) failed to find a significant association of particulate pollution with health in three southeastern schools. However, this may have been due to the index of effect, which was absence rate. Absence is known to be significantly affected by variables other than health.

Epidemiologic studies of U.S. EPA's Community Health and Environmental Surveillance System (CHESS) program have provided dose-effect information on morbidity associated with exposure to sulfur dioxide and other air pollutants. Health indicators employed for long-term effects were prevalence of chronic bronchitis in adults, incidence of acute lower respiratory infection in children, acute respiratory illness in families, and decreases in ventilatory functions of children. The short-term indicators were aggravation of cardiopulmonary symptoms and of asthma. The results support the long-term air quality standards, but indicate that the short-term standards may be too high. CHESS studies have been criticized for inadequate sample size, selected population groupings, and failure to investigate non-respiratory effects. (U.S. EPA, 1974).

The applicability of damage functions observed abroad to U.S. environmental policy decisions is questionable, as comparisons with European data show wide discrepancies. This is illustrated in Figure 7, which reports the relationship between SO_2 concentration and percent excess deaths for New York, London, and Oslo. The two solid lines are drawn through the London and Oslo data, respectively, assuming the existence of thresholds, whereas the corresponding dashed lines make no such assumption. These differences may be due in part to different sampling and analysis techniques, but differences in population characteristics and way of life are probably also significant (Royal Ministry, 1972). Extensive studies in London, where particulate pollution (smoke shade) has decreased more than fivefold in two decades, while SO_2 has only decreased slightly, reveal that the earlier trend of decreasing total and respiratory mortality and morbidity has not been sustained subsequently (Lawther, 1963; Martin, 1964; Fletcher et al., 1968). This is consistent with the situation in New York as reported by Buechley (1975).



Source: Swedish Royal Ministry, 1972

Figure 7. Relationship Between SO_2 Concentration and Excess Deaths in New York, London, and Oslo

3. Nitrogen Oxides

The effects of nitrogen oxides on human health have received relatively little attention, perhaps because of the difficulty of measuring ambient concentrations and the lack of reliable historical data. Consequently, permissible levels of nitrogen dioxide are based on less than adequate evidence.

The best known epidemiologic studies of the effect of nitrogen dioxide (NO_2) on human health were conducted by Shy *et al.* (1970a, 1970b) at Chattanooga, Tennessee, where emissions from a chemical factory provided an opportunity to compare incidence of acute respiratory disease in areas of high, intermediate, and low NO_2 levels. The health data covered the period of 1968-1969, but the corresponding NO_2 data, obtained by the Jacobs-Hochheiser technique, were considered unreliable and were replaced by 1967-1968 NO_2 data measured by the Saltzman method (Shy *et al.*, 1973). The new data are reported in Table 6 for the low and intermediate areas, as well as for the three schools and nearby sampling stations in the high NO_2 area.

Table 6. Respiratory Illness at Various NO₂ Levels in Chattanooga

Areas	Low	Intermediate	High 1	High 2	High 3
NO ₂ , µg/m ³	56	113	282	150	150
Individuals Affected:	Excess Illness, As Percent of Low Area				
All Family	0	- 7.3	18.0	16.7	8.7
Second Graders	0	-10.5	16.4	16.4	1.0
Siblings	0	- 8.2	17.1	5.9	12.4
Mothers	0	- 4.1	24.4	17.1	8.9
Fathers	0	- 8.3	14.6	33.3	26.0

Source: Shy, C.M., et al., 1970a, 1970b, 1973

It should be noted that rates of respiratory disease are not consistently correlated with exposure gradient among the three schools in the high exposure area, whereas rates in the intermediate control area are lower than in the low control area. The results could not be explained by prevalence of chronic conditions, differences in family composition, economic level, or education of family head. Parental smoking habits did not appear to influence respiratory illness rates among children. Meteorological factors were not controlled in the analysis. The study has been criticized by Warner and Stevens (1973) because no attempt was made to control for acid mists, which were probably present in significant concentrations.

A study by Pearlman et al. (1971) of the areas designated by Shy et al., with controls for years of exposure, found that one or more episodes of bronchitis were reported significantly more often by school children residing for two and three years in the high and intermediate NO₂ areas (see Table 7). Neither morbidity from croup and pneumonia, nor reported hospitalization for lower respiratory illness differed significantly among the three areas. In another study at Chattanooga, Chapman et al. (1973) found no association between current or past pollution levels and the prevalence of chronic respiratory disease among parents of high school students residing in three exposure areas.

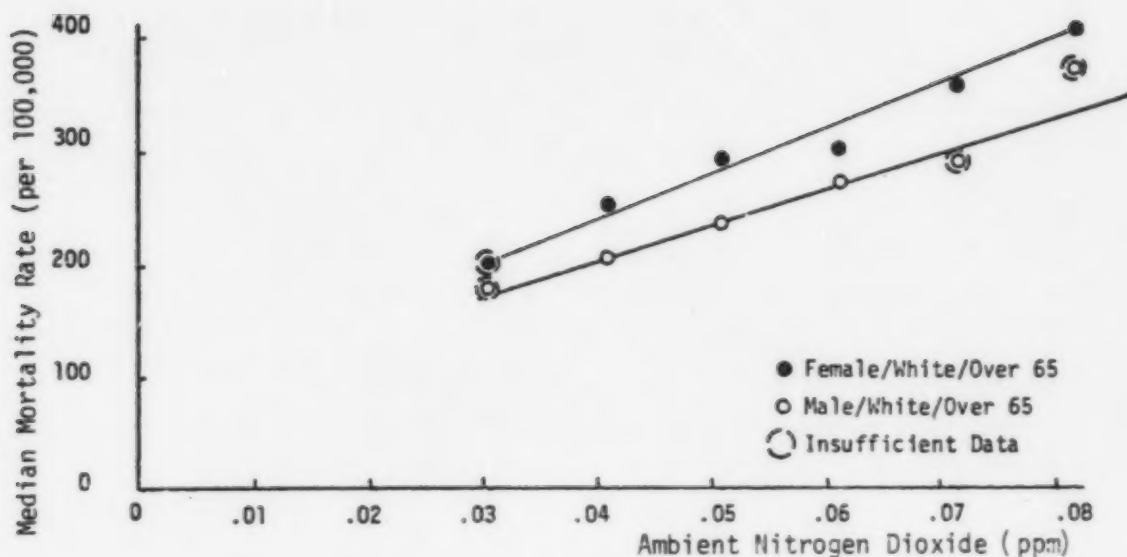
Table 7. Incidence of Bronchitis Among Chattanooga School Children at Various Pollution Levels

Areas	Pollutant				Percent Reporting One or More Episodes		
	NO ₂ (ppm)	Nitrates ($\mu\text{g}/\text{m}^3$)	Sulfates ($\mu\text{g}/\text{m}^3$)	Particulates ($\mu\text{g}/\text{m}^3$)	Years of Exposure		
					1	2	3
Low	.043	1.6	10.0	62	25.1	20.3	23.2
Inter-mediate	.063	2.6	9.8	72	31.6	45.5	31.2
High	.083	5.8	11.5	81	20.9	34.7	32.2

Source: Pearlman, M.F., et al., 1971

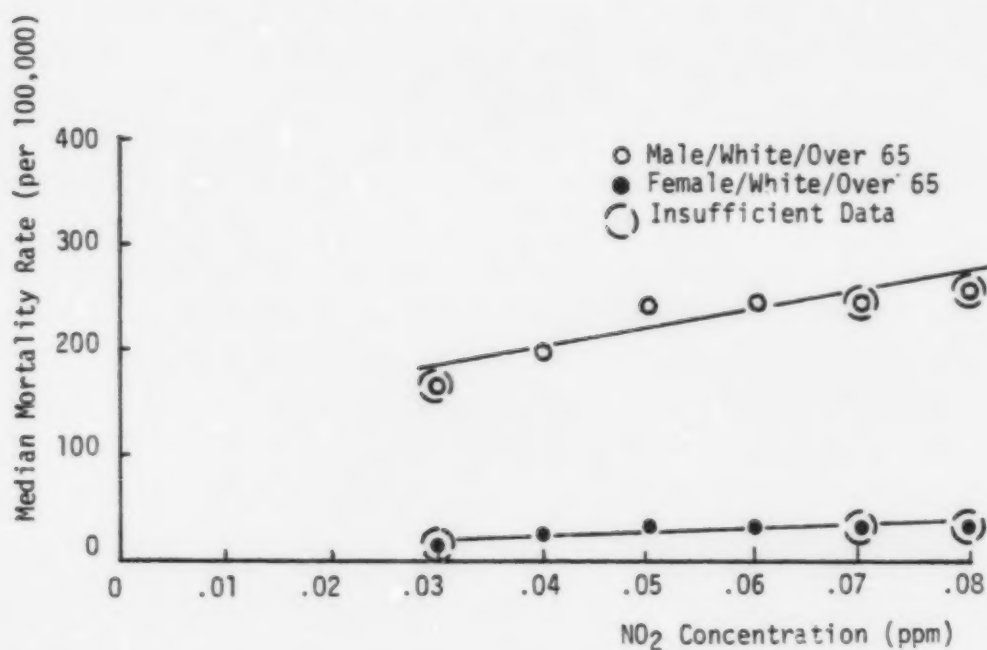
Sprey and Takacs (1973) studied annual data on pollution, climatology, mortality, and socioeconomic characteristics for 42 SMSAs with the aid of single-variable analysis of the median disease-specific mortality rates and found a strong association between NO₂ levels and mortality from hypertensive and arteriosclerotic heart disease and lung cancer (see Figures 8 and 9). Analysis of independent age groups and of pooled variables failed to weaken the association with hypertensive heart disease, but the association with arteriosclerotic heart disease was shown to be due to the interrelationship of nitrogen dioxide levels and ambient sulfate levels. Increases in NO₂ level from 0.3 to 0.8 ppm were associated with approximately 200 more deaths per 100,000 from hypertensive heart disease for white males or females over 65, with 50 and 130 percent increases in lung cancer death rates for white males over 65, and white females over 65, respectively.

Other oxides of nitrogen may have a significant role in pollution chemistry, but the epidemiologic evidence is scarce. Lave and Seskin (1975) found an association between nitric oxide (NO) levels and daily mortality in Chicago as part of their five-city study. Sterling et al. (1966, 1967, 1969) found an association between nitrogen oxides (and other pollutants) in Los Angeles and daily hospital admissions.



Source: Sprey *et al.*, 1974

Figure 8. Relationship Between NO₂ Concentration and Median Mortality from Hypertensive Heart Disease



Source: Sprey *et al.*, 1974

Figure 9. Relationship Between NO₂ Concentration and Median Mortality from Lung Cancer

4. Oxidants

Only two studies of the effects of photochemical oxidants on human health were found to meet all of the selection criteria set forth in Section A 1: a study of school absenteeism by Wayne and Wehrle (1969) and one of student nurses by Hammer et al. (1974).

Wayne and Wehrle (1969) examined the association between daily oxidant levels and school absenteeism at two elementary schools in Los Angeles. They were unable to detect a statistically significant relationship between absences due to respiratory illness and concurrent or previous day's oxidant levels.

Hammer et al. (1974) compared the daily percent of students reporting each of several symptoms in two Los Angeles nursing schools with daily maximum measurements of photochemical oxidants, carbon monoxide, and nitrogen dioxide, as well as temperature. Incidence of symptoms could not be attributed to carbon monoxide, nitrogen dioxide, or maximum temperature. However, threshold functions for symptom rates were developed in relation to photochemical oxidants (see Table 8). The study concluded that the national standard for photochemical oxidants provides little or no margin of safety for the symptoms observed. These findings would have been even more convincing if other factors, such as day-of-the-week effects had been controlled.

Table 8. Oxidant Thresholds For Various Symptoms

Symptom	Oxidant Threshold (ppm)
Headache	0.5
Eye Discomfort	0.15
Cough	0.26
Chest Discomfort	0.30

Source: Hammer, et al., 1974

5. Carbon Monoxide

Effects of carbon monoxide on human health have been investigated almost entirely by toxicological experiments and clinical observations in conjunction with occupational exposure (e.g., of parking attendants, tunnel and toll plaza personnel). Epidemiological studies of carbon monoxide have looked also at oxidants (because of the relation of both to auto exhaust) and other pollutants.

Hexter and Goldsmith (1971) found a significant association between daily mortality in Los Angeles County and levels of carbon monoxide, but no significant association between mortality and oxidant levels. An increase in carbon monoxide level from 7.3 ppm (lowest 24-hour basin average observed during the study period) to 20.2 ppm (highest observed) was eleven deaths for that day. Because the analysis was controlled only for temperature, leaving out other possibly relevant factors, the results should be viewed with caution.

Clinical studies by Aronow et al. (1972, 1973, 1974) have associated carbon monoxide with onset of angina during severe exercise and intermittent claudication. These studies do not yield useful dose-effect functions, but provide supportive evidence.

6. Other Pollutants

Several useful investigations were conducted on the effects of other pollutants or non-specific air pollution. These include a study of the effects of benzo(a)pyrene by Carnow and Meier and of the effects of non-specific air pollution on university students.

A study by Carnow and Meier (1973) of lung cancer mortality in the 48 contiguous United States and in 19 countries concluded that an increase of 1 μg of benzo(a)pyrene in 1000 m^3 of air was associated with an increase of 5 percent in lung cancer mortality. Benzo(a)pyrene levels were estimated on the basis of fuel consumption, rather than direct measurements. This casts strong doubt on the validity of the results.

Durham (1974) investigated the health effects of air pollution on student populations at seven California universities. He controlled for climatic variables and socioeconomic characteristics, as well as confounding factors, such as chronic conditions, prescheduled appointments, weekends, holidays, and exam periods. The data suggest that a 16.7 percent excess in respiratory illness in the form of sore throat, pharyngitis, and tonsillitis among students at University of Southern California over students at University of California at Irvine may have been due to levels of nitric oxide, nitrogen dioxide, and sulfur dioxide that were 3-4 times as high. The similar incidence of common cold symptoms and eye irritation was attributed to the similar levels of photochemical oxidants. No such strong associations between respiratory illness and pollution were found for schools in the San Francisco Bay area.

A report by the California Air Resources Board (Leung *et al.*, 1975) presents a series of dose-effect functions representing the health effects of oxidants, nitrogen dioxide, and carbon monoxide. These were developed on the basis of questionnaires completed by a panel of 14 experts for three age groups and 11 pre-existing disease conditions. The results are of some interest as an expert consensus, but the most significant outcome was the experts' own assessment that, because of lack of adequate data, their judgment was "not trustworthy" in 40 percent of the oxidant, 82 percent of the carbon monoxide, and 92 percent of the nitrogen dioxide values. This lack of confidence by a panel of recognized experts in estimating health effects of various levels of pollution is a salutary reminder that the art of developing dose-effect functions to human health is a long way from being an exact science.

B. DAMAGE TO VEGETATION

The effects of air pollutants on crops and ornamental plants has been the subject of numerous, but inconsistent, investigations. These are surveyed here under the five major pollutants: sulfur dioxide, oxidants, nitrogen oxides, acid rain, and fluorides. Some general remarks about vegetation dose-effect functions precede the survey.

1. General Remarks

Concern over air pollution damage to vegetation has received renewed impetus from the recent discovery of heretofore unsuspected high oxidant levels in rural areas and the completion of investigations indicating substantial crop losses at these levels. The more significant investigations of air pollutant damage to vegetation are listed in Table 9, which specifies the pollutant, plant, type of effect, and author reference. The recent date of these discoveries points up several basic flaws in the studies of vegetation damage, which are delineated briefly here and discussed at greater length in Chapter III (Analytical Methodology).

The principal problems and issues in the development of dose-effect functions in this area are analogous to those encountered for health effects and material damage, but there are significant differences. These are discussed below in terms of:

- Types of studies
- Determination of exposure
- Determination of effect
- Presentation of results

Investigations of the effects of air pollutants on vegetation have been designed primarily to determine susceptibilities of individual plant varieties, rather than to establish a broadly applicable relationship between dose and effect. Consequently, there has been relatively little interest in coordinating the research effort or in setting uniform standards and conditions of investigation that would permit some aggregation or comparison of the results of different studies.

Table 9. Selected Studies of Vegetation Effects of Major Air Pollutants

Pollutant	Plant	Effect	Reference
SO ₂	Ryegrass	Leaf senescence	Bleasdale, 1973
SO ₂	Lichens and mosses	Death	Mansfield & Bull, 1972
SO ₂	Soybeans	Yield reduction	Davis, 1972
SO ₂	Poplar	Leaf injury	Dochinger, 1972
SO ₂	4 ornamental tree species	Leaf necrosis	Temple, 1972
SO ₂ , NO ₂	87 native desert species	Leaf injury	Hill <i>et al.</i> , 1974
SO ₂ , NO ₂	6 crop plant species	Leaf injury	Tingey <i>et al.</i> , 1971
SO ₂ , O ₃	Tobacco	Leaf injury	Menser & Heggstad, 1966
SO ₂ , O ₃	White pine	Needle injury	Linzon, 1966
Acid rain	Tomato	Yield reduction	Kratky <i>et al.</i> , 1974
Acid mist	Yellow birch	Growth reduction	Wood & Borman, 1971
O ₃	Tobacco	Leaf fleck	Heck <i>et al.</i> , 1966
O ₃	Tobacco	Leaf fleck	Turner <i>et al.</i> , 1972
O ₃	Conifers	Needle injury	Davis & Wood, 1972
O ₃	Pine	Photosynthesis reduction	Botkin <i>et al.</i> , 1971
O ₃	Pine	Photosynthesis reduction	Barnes, 1972
O ₃	White pine	Needle injury	Costonis & Sinclair, 1969
O ₃	Ponderosa pine	Needle injury and tree death	Miller, 1973
O ₃	Geranium, carnation	Reduction or delay of flower development	Feder, 1970, 1972, 1973
O ₃	35 crop and ornamental species	Leaf injury	Heck & Tingey, 1971
O ₃	Poinsettia	Reduction or delay of bract development	Feder <i>et al.</i> , 1972, 1973
O ₃ , PAN	Navel orange	Increased fruit drop	Thompson <i>et al.</i> , 1972
PAN	Navel orange	Growth reduction and leaf drop	Thompson & Kats, 1975
O _x	Tobacco	Leaf fleck	Heagle and Heck, 1974
O _x	Potatoes	Yield reduction	Heggstad, 1973
O _x	Cotton	Yield reduction	Brewer & Ferry, 1974
O _x	Corn	Yield and growth reduction	Miller, 1972, 1973
O _x	Corn	Yield reduction	Thompson, 1975
O _x	Spinach, radish, lettuce	Yield reduction	Thompson, 1975
O _x	Lemons	Yield reduction	Thompson & Taylor, 1969
NO ₂	Bean, tomato, tobacco	Weight and chlorophyll reduction	Taylor & Eaton, 1966
NO ₂	Navel orange	No significant effect	Thompson <i>et al.</i> , 1971
NO ₂	Pine and yellow poplar	Growth reduction	Stone & Kelly, 1974
NO ₂ , F ⁺	Citrus trees	Yield reduction	Thompson & Taylor, 1969
F ⁺	Tomato, gladiolus, corn, conifers, citrus, alfalfa, sorghum	Leaf injury, yield reduction	McCune, 1969
F ⁺	Soybeans	Leaf injury, transpiration reduction	Wiebe & Poovaiah, 1973, Poovaiah & Wiebe, 1973

The principal pollutants implicated in substantial damage to vegetation are sulfur dioxide, oxidants, nitrogen oxides, acid rain (probably a dilute solution of sulfuric, nitric, and hydrochloric acids), and fluorides. The determination of response of crops and forests is severely handicapped by the virtual lack of monitoring stations in rural areas. Consequently, ambient levels are determined on the basis of daring interpolations between levels at distant stations or occasional measurements with the aid of portable instruments.

In the past, determination of effects was based largely on measurement of the extent of leaf injury and several indices were developed relating this measure to yield loss. Leaf injury is still considered an important indication of effect in certain plants, such as lettuce and tobacco, because leaf appearance affects saleability. However, substantial losses of fruit, grain, and timber have been found even in the absence of significant leaf injury, so the latter can no longer serve as an indiscriminate proxy for yield loss. An additional undetermined amount of yield loss occurs when more resistant plant varieties are substituted for the more susceptible ones, which tend to be more productive.

Effects of air pollutants on vegetation exhibit wide variations among the various species and as a result of differing genetic and environmental conditions. The latter include stage of growth, general viability and vigor, temperature, humidity, amount of insolation, soil moisture and acidity, and availability of nutrients. These are much more important here than in the case of human health effects, where the target population belongs to one species and genetic and environmental conditions are controlled within a more narrow range.

Most applications of dose-effect functions in the decision-making process require aggregation of effect measures over large target populations and geographic areas. Efforts to satisfy these requirements have been frustrated largely by the wide variations of study results and by their basic incomparability, which was mentioned earlier. There have been some attempts to alleviate the problem through the

construction of data envelopes and/or scatter diagrams, which provide a very gross indication of the direction and order of magnitude of the effect as a function of exposure.

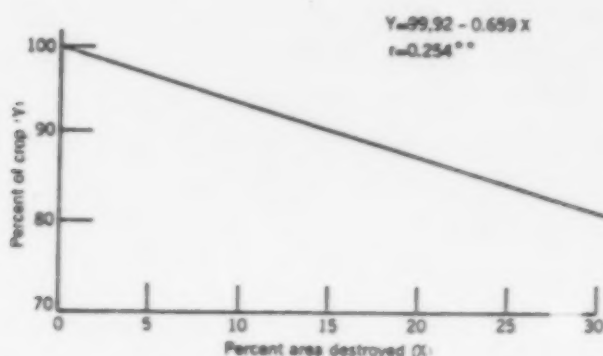
In conclusion, the state of development of consistent and broadly applicable dose-effect functions relating exposure to air pollutants with vegetation damages is considerably less advanced than that in the areas of health effects or materials damages. The major reasons are the scarcity of air quality records in rural areas, some lack of foresight and coordination in the design of investigations and presentation of results, but most of all, the broad variety of target species and the ensuing variability of effects.

2. Sulfur Oxides

Early studies identified sulfur dioxide as the primary factor in air pollution damage to vegetation, and many of these have developed quantitative relationships between SO_2 levels and plant injury, or yield loss. More recent investigations have examined the effects of acid rain and mist. Dose-effect functions of single plant species have been investigated for ryegrass (Bleasdale, 1973), soybean (Davis, 1972), and poplar (Dochinger, 1972). More diversified studies have focussed on ornamentals (Temple, 1972), mosses and lichens (Mansfield and Bull, 1972), and a variety of desert species (Hill *et al.*, 1974).

Exposure of ryegrass to sulfur dioxide in coal smoke was found to reduce plant weight between 16 and 57 percent (Bleasdale, 1973). Earlier leaf senescence was also observed in plants exposed to ambient SO_2 . The reliability of the SO_2 data is in question due to the imprecise measurement of ambient pollutants. Moreover, the coal smoke may well contain various particulate fractions capable of producing damage.

The relationship between leaf injury and yield loss has been investigated by Davis (1972) in a three-year study involving 485 plots of soybeans. Sulfur dioxide fumigations were carried out at two growth stages during the first two years, and at seven growth stages during the last year. A strong correlation was found between leaf area destroyed and reduction of yield (see Figure 10). However, no direct link has been established between SO_2 concentration and yield, though there are indications that the raw data could provide this information.

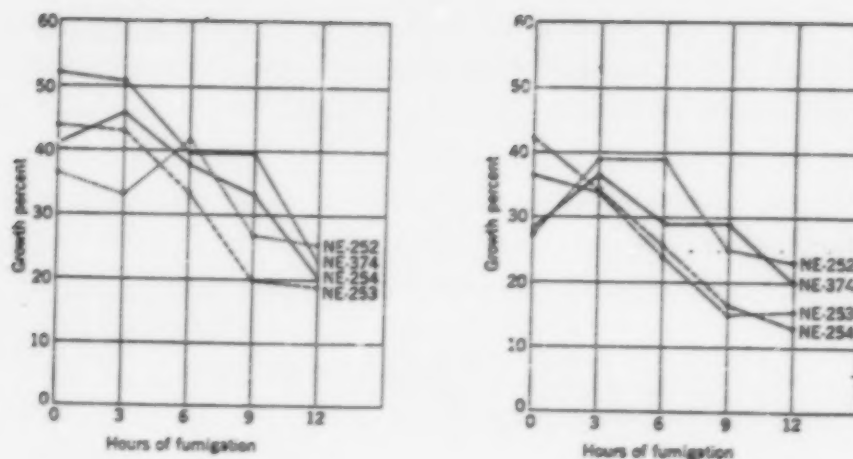


Source: Davis, 1972

Figure 10. Correlation of Soybean Yield with Leaf Area Destroyed

The effect of sulfur dioxide fumigation on a special variety of hybrid poplar was documented by Dochinger *et al.* (1972). Fumigation was carried out at 5 ppm for 0, 3, 6, 9, and 12 hours in controlled environment chambers. Results were plotted as percent leaf injury vs. hours of fumigation for both lower and upper shoots and various clonal variations within the species (see Figure 11). The results provide a good damage function at fixed concentration, but the extension to other concentrations and the applicability to other species is very limited.

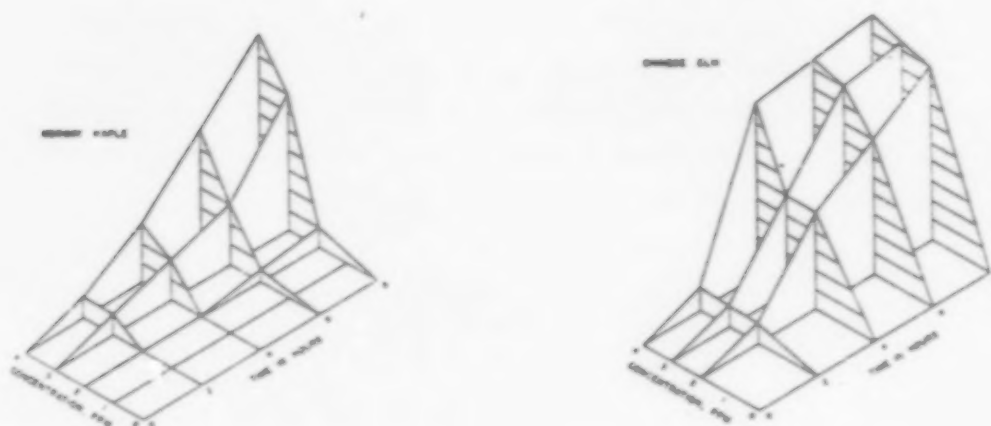
Air pollution may cause substantial damage to ornamental plants, leafy vegetables, and native vegetation through foliar injury alone. Ornamentals are used for their aesthetic value, and hence, deterioration in plant appearance reduces its saleability. Native species may not have an assigned economic value, but destruction of their foliage is likely to reduce aesthetic enjoyment or to produce increased erosion.



Source: Dochinger et al., 1972

Figure 11. Relationship Between Length of Exposure to SO_2 and Growth of Upper (left) and Lower (right) Shoots for Various Poplar Clones

Effects of sulfur dioxide exposure of four species of ornamental trees were investigated by Temple (1972) with the aid of controlled environmental chambers. Some results are plotted in Figure 12 in the form of a three-dimensional surface representing degree of leaf necrosis as a function of both time and concentration. Accuracy of the results is within 5-10 percent.



Source: Temple, 1972

Figure 12. Three-Dimensional Relationship Between Exposure to SO_2 and Leaf Necrosis in Norway Maple and Chinese Elm

In a massive study of the effects of power plant emissions on native vegetation, Mansfield and Bull (1972) found that lower plant types, such as lichens and mosses, suffer extensive damage or death at SO_2 concentrations as low as 0.01 ppm. This is due to the concentration of toxic substances in the plant tissue over long periods of time, coupled with the fact that these plants take up airborne substances to support a portion of their nutrient requirements.

Hill et al. (1974) fumigated some 80 species of desert plants with sulfur dioxide and a combination of SO_2 and NO_2 in portable environmental chambers. Most of the species were found to be resistant to two-hour exposures at concentrations up to 2 ppm, but some foliar injury appeared at higher levels up to 7 ppm. Moreover, no synergistic effect was observed at the levels used.

Investigations of SO_2 injury to white pine near a smelter were coupled with ozone fumigation to determine whether either pollutant was responsible (Linzon, 1966). Exposures to SO_2 levels of 0.25 ppm for several hours were found to cause injury, as were O_3 concentrations of 0.60 ppm for 2-4 hours. The combined effect of these pollutants, however, was not investigated carefully.

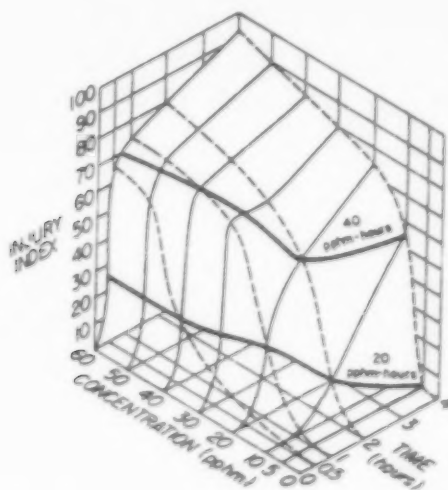
On the other hand, distinct synergistic effects have been observed upon exposure of tobacco to acute fumigations with both SO_2 and O_3 (Menser and Heggstad, 1966). Three cultivars of tobacco showed no leaf damage upon exposure to 2-4 hours of 0.03 ppm O_3 levels and 0.24 ppm SO_2 . However, when these concentrations were used together, 38 percent of the leaf area suffered damage after a 2-hour fumigation and 75 percent after a 4-hour fumigation. The corresponding leaf areas damaged were 15 and 41 percent, respectively.

3. Oxidants

Effects of photochemical oxidants, including ozone, have attracted a great deal of attention, especially in the wake of the recent discovery of high oxidant levels in rural areas. Most investigations have been directed at field crops, such as alfalfa, broccoli, clover, corn, cotton, cucumbers, lettuce, oats, potatoes, radishes, sorghum, spinach, tobacco,

and tomatoes (Heck et al., 1966; Heck and Tingey, 1971; Feder, 1973; Turner et al., 1972; Heggstad, 1973; Heagle and Heck, 1974; Brewer and Ferry, 1974; Thompson, 1975). Other studies dealt with citrus trees (Thompson and Taylor, 1969; Thompson et al., 1972; Thompson and Kats, 1975), coniferous lumber trees (Costonis and Sinclair, 1969; Botkin et al., 1971; Barnes, 1972; Davis and Wood, 1972; Miller, 1973), and such ornamental plants as carnations, geraniums, and poinsettias (Feder, 1970; Feder, 1973; Feder et al., 1972).

The first major crop plant to be investigated was the experimental and highly susceptible Bel W-3 tobacco cultivar. Heck et al. (1966) showed that varying exposures of up to 60 ppm of ozone for four hours may cause more than 90 percent leaf injury. The results were plotted in a three-dimensional surface representing an injury index as a function of both exposure time and concentration (see Figure 13).



Source: Heck et al., 1966

Figure 13. Three-Dimensional Relationship Between Exposure to Ozone and Injury to Bel W-3 Tobacco

Turner et al. (1972) assessed directly ozone damage to tobacco by measuring height, dry weight, leaf area, amount of fleck injury, as well as total leaf stomatal conductance, an indirect measure of photosynthesis and respiration. Four cultivars of varying sensitivity were grown under field conditions during both years of the study and in greenhouses during the second year. The air quality data specifies both diurnal variations

and daily peak oxidant readings throughout the growing season. The uninjured leaf area for the most tolerant (6524) and the most sensitive (Bel W-3) cultivars was determined to be 10 and 71 percent, respectively, in the presence of ozone, and 10 and 14 percent, respectively, in filtered air. Standard errors are reported for most of the results.

The predisposition to injury from previous exposure was investigated by Heagle and Heck (1974), again for the Bel W-3 cultivar. Plants exposed to seven days of continuous high oxidant levels exhibited more than twice as much injury as the total of seven plants exposed for only one day each. The postulated mechanisms for the cumulative injury are progressive accumulations of toxic substances, progressive degradation of cell membranes, or a gradual disruption of enzyme processes. The eight week mean total injury per leaf indices were found to be twice as high for continuous groups as for daily exposure groups.

In a similar set of experiments, Heck and Tingey (1971) obtained acute injury indices as a function of exposure time and concentration for a number of crop and ornamental plants. The plants were exposed to .075 - 1.0 ppm ozone levels for periods of up to seven hours. Typical results for the more important varieties are shown in Table 10.

Table 10. Ozone Injury to Selected Plants

Plants	Injury Index											
	1.0 hr				2.0 hr				4.0 hr			
	7.5	15	30	60	7.5	15	30	60	7.5	15	30	60
	pphm	pphm	pphm	pphm	pphm	pphm	pphm	pphm	pphm	pphm	pphm	pphm
Tomato, Roma	>1	19	63	—	1	52	91	—	10	35	63	—
Broccoli, Calabrese	2	>1	15	—	0	3	61	—	0	2	66	—
Spinach, Northland	0	0	1	—	0	0	23	—	0	3	77	—
Sorghum, Martin	—	>1	7	50	—	4	48	73	—	36	44	96
Red Clover, Pennacott	—	1	7	41	—	0	33	60	—	16	29	84
Cucumber, Long Markerer	—	0	2	18	—	0	6	9	—	1	7	18

Source: Heck and Tingey, 1971.

Potatoes have exhibited up to 50 percent reduction in yield in Maryland upon exposure to oxidant levels above 0.05 ppm. Heggestad (1973)

has reported on a number of potato cultivars, with yields of the Haig and Norland varieties being reduced most significantly. These yield losses were shown to be at least qualitatively related to leaf injury.

Effects of oxidant exposure on cotton yield in the San Joaquin Valley were studied during a two-year period in four locations by Brewer and Ferry (1974). Cotton grown in filtered air was found to produce 10-30 percent more yield than control plants grown in chambers containing unfiltered air or those grown on the outside (see Table 11).

Table 11. Effects of Oxidants on Cotton Yield

Location	Plot	1972 Yields		1973 Yields	
		Bolls/ plant	Wt. of lint & seed gm	Bolls/ plant	Wt. of lint & seed gm
Parlier	Outside	7.5	53.8	10.2	44.1
	Ambient air	7.6	55.3	8.6	55.7
	Filtered air	9.5	68.3	12.4	78.6
Hanford	Outside	15.0	101.8	9.4	65.8
	Ambient air	14.6	99.0	7.4	47.6
	Filtered air	18.8	124.3	9.5	58.3
Fire Points	Outside	11.1	75.3	12.2	83.7
	Ambient air	11.0	76.9	9.8	63.9
	Filtered air	12.7	82.9	10.9	67.2
Cotton Center	Outside	...	...	8.2	49.3
	Ambient air	...	...	6.0	30.7
	Filtered air	...	...	7.5	41.8

Source: Brewer and Ferry, 1974

Effect on corn yield has been studied in New England (Feder, 1972) and in California (Thompson, 1975). Feder found that corn exposed to pollutant levels of approximately 0.10 ppm for seven hours per day, five days per week, suffers a reduction of 30 percent in leaf area, 20 percent in stem length, 32 percent in ear weight, and 60 percent in number of filled kernels per ear. Thompson reported significant yield reductions for two cultivars of corn. In the case of Monarch Advance, a susceptible variety, fresh weight per husked ear was reduced by 28 percent by exposure to ambient smog over the growing season. For Bonanza corn, a more resistant variety, ear weight was only slightly affected, but the number of second ears was reduced by 75 percent when compared with plants grown in filtered air. Other effects of the controlled greenhouses may have accounted for a portion of the yield reduction.

Thompson (1975) also found major reductions in plant weight for spinach, radish, and lettuce grown under varying concentrations of photochemical smog. The results are reported in Table 12.

Table 12. Yield of Several Vegetables Exposed to Various Levels of Photochemical Smog

Index Ambient Smog	Spinach		Radish		Lettuce	
	Plant wt. (grams)	Percent	Plant wt. (grams)	Percent	Plant wt. (grams)	Percent
0	37.1	100	8.4	100	549	100
25	38.6	104	8.8	104	525	96
50	31.6	85	7.7	92	491	89
75	31.8	86	7.2	86	401	73
100	18.6	50	5.2	62	317	58

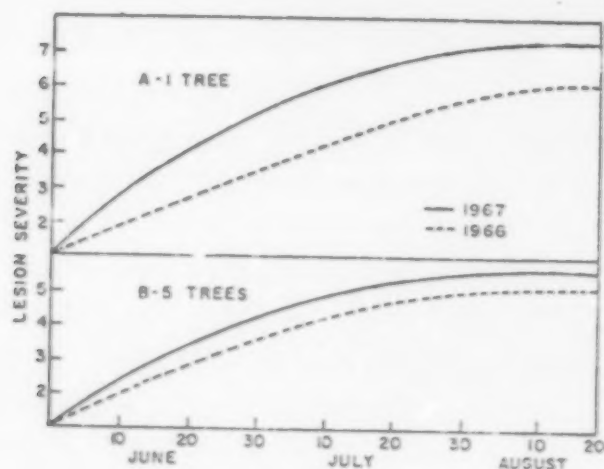
Source: Thompson, 1975

The yield of lemons was found to be significantly affected by ozone and nitrogen dioxide in ambient smog, but the effect of component pollutants was not adequately isolated (Thompson and Taylor, 1969). In a similar fashion, exposure of navel orange trees to both ozone and peroxyacetyl nitrate have shown that ozone alone causes little damage, but peroxyacetyl nitrate and photochemical smog produce significant increases in fruit drop.

The most extensive survey of the effects of oxidants on coniferous trees has been performed by Davis and Wood (1972). The study focused on leaf injury to new growth in 2-6 year-old seedlings, which may affect the photosynthesis process, and hence, the eventual growth of the trees. Six species of pine (*Pinus*), two of larch (*Larix*), and eastern hemlock (*Tsuga canadensis*) were found to be susceptible to 8-hour exposures to 0.25 ppm ozone levels every two weeks. Nine other coniferous species including four spruce (*Picea*), two fir (*Abies*), Douglas fir (*Pseudotsuga menziesii*), *Aborvitae* (*Tsuga occidentalis*), and red pine (*Pinus resinosa*) were found to be resistant to damage at these levels.

Studies measuring photosynthesis more directly in three species of yellow pine have been performed by Botkin *et al.* (1971) and Barnes (1972). Barnes' results indicate that photosynthesis is sometimes enhanced at ozone levels up to 5 pphm, but extended exposures to 15 pphm levels reduces CO₂ exchange in most cases. Botkin, on the other hand, found that much higher doses in experimental chambers had no significant effects in producing either visible symptoms or reduction of photosynthesis.

Costonis and Sinclair (1969) investigated ozone injury to white pine (*Pinus strobus* L.) in both controlled environment and portable polyethylene chambers. More significant in terms of extended injury were their field measurements on development of symptoms over a two-year period. Highest four-hour mean ozone concentrations varied from 0.044 to 0.052 ppm in 1966 and 0.05 - 0.085 ppm in 1967. Corresponding injury manifested by necrotic lesions on the needles and measured on a scale of 1-8 are shown in Figure 14 for a single highly susceptible tree (A) and five normal trees (B).



Source: Costonis and Sinclair, 1969.

Figure 14. Ozone Injury to White Pine Needles as a Function of Time for Two Years with Different Ozone Levels for a Single Susceptible (A) and Five Normal (B) Trees.

Ozone damage to Ponderosa pine was studied by Miller (1973) in the San Bernardino National Forest. The trees suffered an 8 percent mortality rate over a three-year period as compared to a normal rate of less than 3 percent. They finally succumbed to attack by bark beetles after being weakened by ozone.

Carnation, geranium, and poinsettia cultivars have all been found susceptible to damage by ozone (Feder, 1970; Feder *et al.*, 1972; Feder, 1972). Plants grown to maturity in 0.10 - 0.12 ppm ozone concentrations showed reductions or delays in bract or flower development, as well as depressed growth. Average leaf area was reduced by 10 percent in geranium and bract area decreased by 39 percent in poinsettia grown in air containing 0.12 ppm ozone. This exposure constituted a higher average dose than would be experienced under ambient conditions due to ambient diurnal fluctuations. Carnation showed significant delay in flower bud initiation in 0.10 ppm ozone, but otherwise, bud development was not affected.

4. Nitrogen Oxides

Investigations of the effects of nitrogen oxides on vegetation have suffered from several handicaps, including the numerous atmospheric reactions of the several oxides, the rapid fluctuations of their ambient levels, the lack of an acceptable measurement techniques, and the synergistic effects with sulfur dioxide and oxidants. Most studies have attempted to circumvent these problems by adopting nitrogen dioxide (NO_2) as a proxy for all nitrogen oxides and by relying on controlled laboratory exposures or on concentration predictions based on emission levels. Principal studies have examined the effects on pinto bean, tobacco, and tomato (Taylor and Eaton, 1966), navel orange (Thompson *et al.*, 1971), and pine trees (Stone and Skelly, 1974).

Effects of nitrogen dioxide exposures on pinto bean, tobacco and tomato were investigated by Taylor and Eaton (1966) in temperature-controlled fumigation chambers. Several cultivars of tobacco exhibited leaf damage after nine-hour exposures to $4.72 \text{ mg/m}^3 \text{ NO}_2$ levels, but there was no damage after five-hour exposures. Results of longer exposures at lower concentrations, closer to ambient levels of pinto bean and tomato, are shown in Tables 13 and 14. Significant differences in weight and chlorophyll content were observed for exposures over 10 days to levels between $0.61 - 1.03 \text{ mg/m}^3$.

Table 13. Effect of NO_2 Exposure on Growth Rate of Pinto Bean Seedlings and Chlorophyll Content of Primary Leaves

Days exposed	Conc. NO_2 (mg/m^3)	Chlorophyll content (mg/g)							
		Fresh weight (g)		Dry weight (g)		Fresh weight (g)		Dry weight (g)	
		NO_2	Check	NO_2	Check	NO_2	Check	NO_2	Check
10	0.62	1.41	1.94*	0.110	0.141*	2.25	1.64*	25.4	22.9*
19	0.62	3.85	4.53*	0.382	0.423*	2.25	1.90*	24.95	21.58**
11	0.62	1.76	2.06*	0.195	0.208**	3.01	2.40*	27.12	23.52*

* Significant difference at 1% level.
 ** No significant difference.

Statistical analysis by t test; N = 20

Source: Taylor and Eaton, 1966

Table 14. Effect of NO_2 Exposure on Growth of Pearson Improved Tomato Plants

Days exposed	Conc. NO_2 (mg/m^3)	Fresh weight (g)		Dry weight (g)	
		NO_2	Check	NO_2	Check
10	0.31-0.43	14.3	18.0*	0.10	0.15*
14	0.53-1.17	2.3	2.8**	0.17	0.18***
19	0.82-1.03	8.7	10.6*	0.66	1.04**
22	0.27-0.53	6.22	7.94**	0.47	0.59**

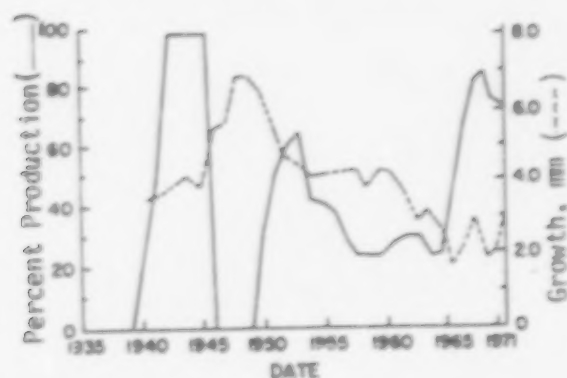
* Significant difference at 5% level.
 ** Significant difference at 1% level.
 *** No significant difference.

Statistical analysis by t test; N = 20

Source: Taylor and Eaton, 1966

Thompson et al. (1971) exposed navel orange trees to NO_2 concentrations up to twice ambient levels. Leaf drop was compared with that of control trees exposed to carbon-filtered air. The slightly higher leaf drop from trees exposed to NO_2 was determined to be statistically insignificant. Although the data cannot be used to develop a damage function, they do suggest the presence of a threshold.

An ingenious, but not very successful attempt to determine the relationship between NO_2 emission levels and amount of growth in 43 white pine trees near Radford, Virginia was made by Stone and Skelly (1974). The NO_2 levels were estimated on the basis of production volume in the nearby Radford Army Ammunition Plant, a major local source of nitrogen oxides. Growth rates were determined by measuring the width of the annual growth ring. The inverse correlation shown in Figure 15 is not very convincing and suggests either a poor relationship between production and NO_2 levels, or the presence of other growth-stunting factors or, most likely, both.



Source: Stone and Skelly, 1974

Figure 15. Relationship Between NO_2 Emissions Represented by Ammunition Plant Production and Growth Rate of White Pine Trees

5. Acid Rain

Acid rain is formed when rain drops scavenge sulfuric, nitric and hydrochloric acids from airborne aerosols and its severity is measured by its pH. Acid rain has been recently brought to light as a

serious environmental problem in Europe (RMFA, 1972) and in the eastern U.S. (Likens and Borman, 1974). Measurements of pH between 3.0 and 4.0 have been rather frequent, and values as low as 2.0 have been reached.

Studies in Hawaii reported that certain tomato plants grown under rain shelters averaged 5 kg per plant of saleable fruit, whereas plants grown in the natural rainfall yielded no saleable fruit due to blossom drop, poor fruit set, or reductions in fruit quality (Kratky *et al.*, 1974). A pH drop from 5.0 to 4.5 in the rainwater caused a reduction in pollen tube germination (a necessary prerequisite for fruit growth) from 5.3 to 2.2 percent.

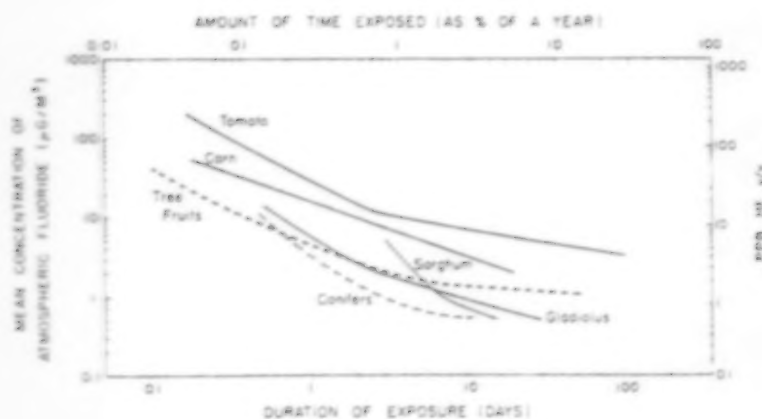
Yellow birch seedlings exposed to acid mist under greenhouse conditions showed marked decreases in estimated weight when pH dropped below 3.0 and significant mortality rate at pH 2.3 (Wood and Borman, 1974). The acid mist treatments were applied for one six-hour period each week over a period of 120 days to simulate natural conditions.

6. Fluorides

Fluorides are emitted during production of aluminum, steel, ceramics, and phosphate fertilizers, and thus, present a localized pollution problem. Gaseous hydrogen fluoride is taken up and accumulated by the plant's leaves, though particulate fluorides also play a role. Fluoride injury is thought to take place through direct interaction with plant enzymes or tissues, or through induced changes in cellular nutrient and hormone balance (McCune and Weinstein, 1971).

Threshold levels of foliar injury and yield reduction have been charted for conifers, corn, gladiolas, sorghum, tomato, and tree fruits by McCune (1969). His results show that even between such diverse plant types as tomato and conifers, threshold levels for any particular length of exposure fall within a factor of ten and they are much closer for other plants (see Figure 16). More detailed information on the individual species has been reported by the National Academy of Sciences (NAS, 1971). Relations between fumigation levels and total fluoride content has been derived for

alfalfa and a number of other forage crops. Although these threshold values are important, the establishment of useful damage functions will require quantification of yield reduction as a function of varying concentrations over the growing season.



Source: McCune, 1969

Figure 16. Threshold Levels of Foliar Injury and Yield Reduction for Several Plants.

Other studies have shown that fluoride uptake and effects are influenced by moisture, temperature, and sunlight (Poovaiah and Weibe, 1973). Soybeans exposed to 15 ml/l fluoride levels for four days exhibited 60-70 percent reductions in transpiration rate, whereas exposures of six hours per day produced lesser reductions. These effects correlated qualitatively with the extent of observed foliar injury. Drought conditions before exposure were found to reduce subsequent fluoride injury due to decrease stomatal uptake, while post-fumigation drought increased injury (Poovaiah and Weibe, 1973). Conditions of high temperature or sunlight were also found to accelerate foliar injury by as much as 40 percent.

C. DAMAGE TO MATERIALS

Investigations of the effects of air pollutants on materials are less complicated than those of health or vegetation effects, because of the opportunity to control both exposure and the target population. Nevertheless, useful dose-effect functions in this area are not many. This section examines the effects of sulfur dioxide, particulates, and nitrogen dioxide and ozone, following some introductory general remarks.

1. General Remarks

Investigation of the effects of air pollutants on materials permits the control of both exposure and the makeup of the target population. Nevertheless, useful dose-effect functions in this area are largely confined to representations of the corrosion of metals by sulfur oxides and the soiling of exposed surfaces by particulates. Other pollutants studied include particulates, nitrogen oxides, and oxidants. Target populations are paper, textiles, leather, paints and dyes, rubber, plastics, metals, ceramics, and stone (see Table 15).

Effects of long-term exposures have been determined by exposing test panels to ambient conditions for long periods of time. The results of these field studies have been flawed by poor ambient level measurements and failure to account for other pertinent environmental variables. Laboratory studies have attempted to determine short-term effects by subjecting test panels to elevated pollutant concentrations. Recent laboratory experiments have employed more realistic concentrations. Humidity exerts a major influence on the severity of most effects, with temperature and air flow playing lesser roles.

Since most materials of interest are available in a great variety of compositions and physical and chemical characteristics, it is not surprising that effects of a given pollutant under a specified set of conditions may vary widely from one material to another. For this reason, the target population must be specified accurately, as was the case with health and vegetation effects. On the other hand, the close similarity between different samples of the same material affords a high degree of precision and the determination of standard errors on

Table 15. Selected Studies of Material Effects of Major Air Pollutants

Pollutant	Material	Effect	Reference
SO ₂	Steel	Corrosion	Sereda, 1960
SO ₂	Steel	Corrosion	Haynie and Upham, 1971
SO ₂	Zinc	Corrosion	Guttman, 1968
SO ₂	Zinc	Corrosion	Dunbar, 1968
SO ₂	Zinc	Corrosion	Haynie and Upham, 1970
SO ₂	Aluminum	Corrosion	Azis and Godard, 1959
SO ₂	Copper	Corrosion	Mattsson and Holm, 1968
SO ₂	Nickel and titanium alloys	Corrosion	Van Rogen and Copson, 1968
SO ₂	Nickel and titanium alloys	Corrosion	Greenlee and Plock, 1968
SO ₂	Cotton fabric	Reduction in tensile strength	Brysson <i>et al.</i> , 1967
SO ₂	Limestone and marble	Decay	Gauri and Sarma, 1973
SO ₂ , NO ₂ , O ₃	Aluminum	Corrosion-induced cracking	Haynie, 1975
SO ₂ , NO ₂ , O ₃	Paints	Erosion	Spence <i>et al.</i> , 1974
SO ₂ , NO ₂ , O ₃	Cellulosic fabric	Dye fading	Upham <i>et al.</i> , 1974
O ₃	Paints	Erosion	Spence <i>et al.</i> , 1974
Particulates	Paints	Increased maintenance	Michelson and Tourin, 1967
Particulates	Paints	No significant maintenance change	Booz, Allen and Hamilton, 1970
Particulates	Paints and exposed	Decrease in reflectance	Beloin and Haynie, 1973
Particulates	Electrical contacts	Tarnishing	Campbell, 1972
Particulates	High-voltage insulators	Flashover and current leakage	Robinson, 1972
Particulates	Electronic components	Failure	Baker, 1975

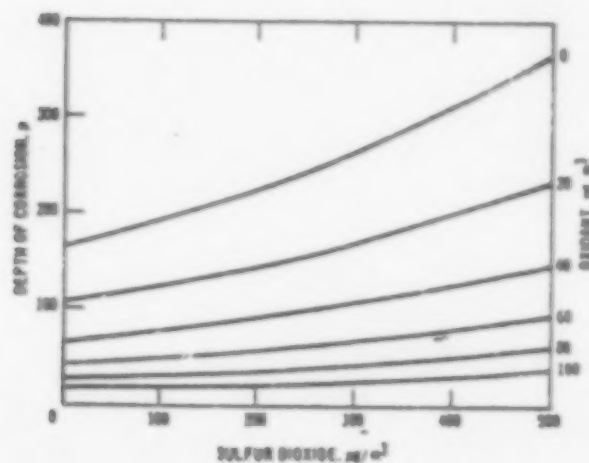
the basis of replicate experiments. Results are typically expressed in terms of percentage loss of useful life or increased frequency of maintenance and replacement.

2. Sulfur Oxides

Sulfur oxides in the presence of moisture and oxidants, probably in the form of sulfuric acid, has been found responsible for the corrosion of metals, damage to electrical contacts, deterioration of paper,

textiles, leather, finishes and coatings, and erosion of building stone through conversion of calcium carbonate to the soluble sulfate. Investigations of metals have focused on steel (Sereda, 1960; Haynie and Upham, 1971), zinc (Dunbar, 1968; Guttman, 1968; Haynie and Upham, 1970), aluminum (Azis and Godard, 1959; Haynie, 1975), copper (Mattsson and Holm, 1968), nickel (Van Rooyen and Copson, 1968), and titanium (Greenlee and Plock, 1968).

Haynie and Upham (1971) exposed three types of steel at eight urban sites to determine correlations between sulfur dioxide and nitrogen oxide and oxidant levels with corrosion of the metal. They found that corrosion increased with higher sulfur dioxide levels, but decreased with rising oxidant concentrations, which apparently acted antagonistically toward sulfur dioxide. The results of the investigation are presented in Figure 17 as a family of curves representing different oxidant levels and a plot of depth of corrosion vs. sulfur dioxide concentration over a ten-year period.



Source: Haynie and Upham, 1971

Figure 17. Relationship Between SO_2 and Oxidant Concentrations and Depth of Corrosion of Carbon Steel.

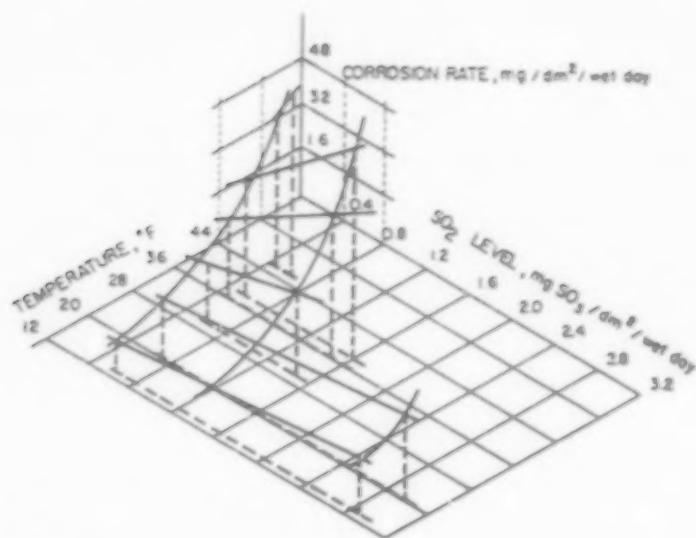
Sereda (1960) found significant synergistic effects of SO_2 and temperature on corrosion of steel. The results are plotted in Figure 18 as a three-dimensional surface representing corrosion rate as a function of both SO_2 concentration and temperature. The surface was then approximated by a plane and its equation was formulated to least squares fit as follows:

$$Y = 0.131x + 0.018z + 0.787,$$

where Y = log corrosion rate, in $\text{mg}/\text{dm}^2/\text{wet day}$

x = SO_2 pollution rate, in $\text{mg SO}_3/\text{dm}^2/\text{day}$

z = average monthly temperature during wet days, in $^{\circ}\text{F}$.

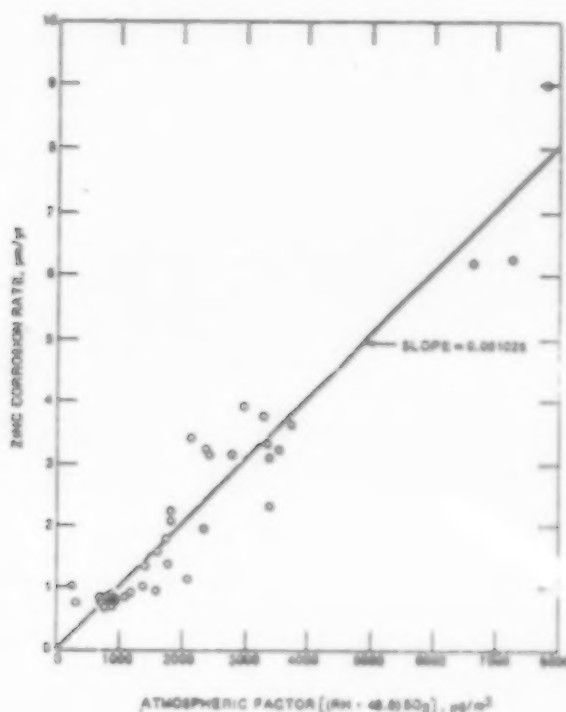


Source: Sereda, 1960

Figure 18. Three-Dimensional Relationship Between SO_2 Level, Temperature and Corrosion Rate of Steel.

The importance of zinc is related to that of steel because zinc is used in the galvanization process to protect steel. An initial investigation by Guttman (1968) disclosed that SO_2 , relative humidity, and to some extent, temperature affects corrosion in raw zinc. Another study by Dunbar (1968) found no significant difference in weight loss among three

grades of zinc ranging in purity from 99 - 99.9% upon exposure to SO_2 and moisture. In the experiment cited earlier for steel, Haynie and Upham (1970) exposed test samples in eight urban areas and found a linear relationship between corrosion rate and an atmospheric factor composed of SO_2 concentration and relative humidity (see Figure 19). This study is described in greater detail in Section IV D.

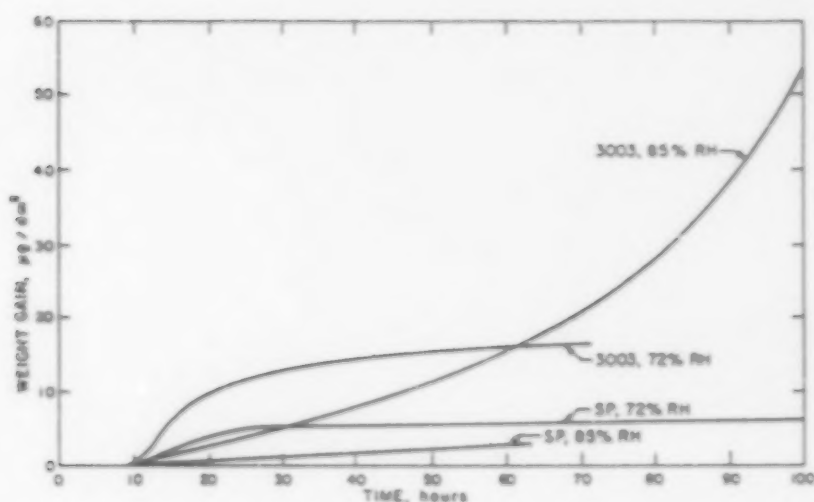


Source: Haynie and Upham, 1970

Figure 19. Relationship Between SO_2 Concentration, Relative Humidity, and Corrosion Rate of Zinc.

Azis and Godard (1959) investigated the corrosion of aluminum under laboratory conditions at SO_2 levels of 280 ppm. The results are displayed in Figure 20 as a family of curves representing several alloys and different levels of relative humidity on a plot of weight gain due to corrosion vs. time. Unfortunately, the study fails to relate corrosion rate with varying SO_2 concentrations.

The effects of SO_2 , NO_2 , and ozone on corrosion-induced cracking in aluminum were investigated by Haynie (1975). The bending strength of the metal was found to decrease with increasing concentration of SO_2 . The particular alloy under study had been stressed for over 2,000 hours at the relative humidity of 80% and a temperature of 29°C .



Source: Azis and Godard, 1959

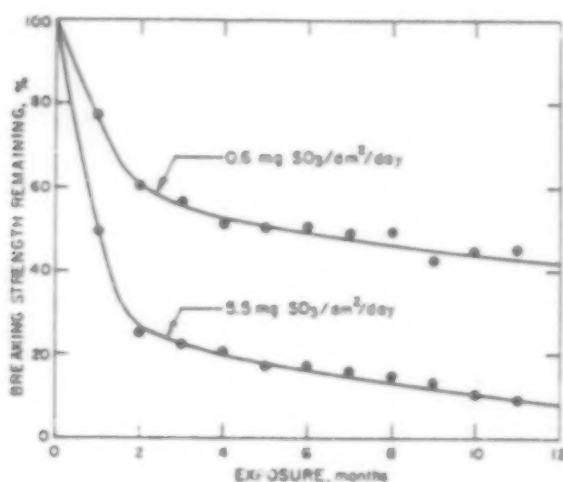
Figure 20. Relationship Between SO_2 Exposure Time and Corrosion Rate of Two Aluminum Alloys at 72 and 85 Percent Relative Humidity and 280 ppm SO_2 concentration.

Copper and its alloys have been investigated in a less quantitative fashion. A study by Mattsson and Holm (1960) reported corrosion rates of $0.2\text{--}0.6\text{ }\mu\text{m/year}$ at SO_2 concentrations of $8\text{ }\mu\text{g/m}^3$ and of $0.9\text{--}2.2\text{ }\mu\text{m/year}$ at SO_2 levels of $70\text{ }\mu\text{g/m}^3$.

Studies of nickel and titanium alloys by Van Rooyen (1968) and by Greenlee and Plock (1968) found most of these metals highly resistant to air pollutants, even in heavily industrial atmospheres.

The more significant studies of the effects of SO_2 exposure on other materials were performed on cotton fabrics (Brysson *et al.*, 1967), carbonate stone (Gauri and Sarma, 1973), and four types of paints (Spence *et al.*, 1974).

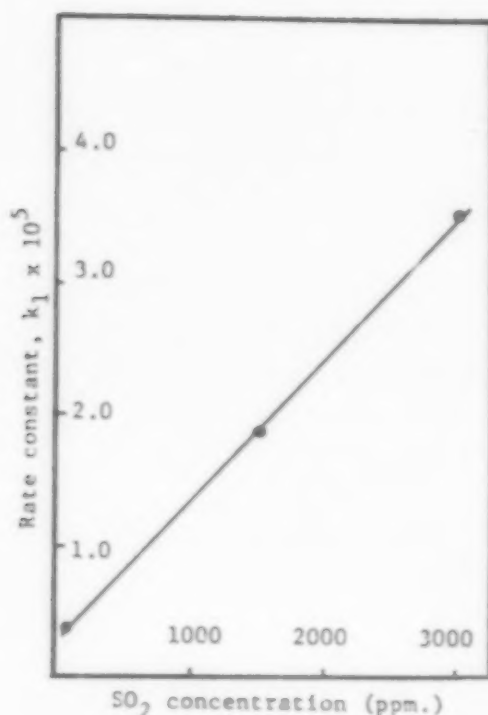
Brysson exposed cotton fabrics to sulfates at seven locations in the St. Louis area and found significant reduction in their service life. The results are plotted in Figure 21 in the form of tensile strength vs. time of exposure at two levels of SO_3 .



Source: Brysson *et al.*, 1967

Figure 21. Relationship Between SO_2 Exposure Time and the Tensile Strength of Cotton Fabric at Two Levels of SO_3 .

Effects of SO_2 exposure in the presence of moisture on carbonate stone, including limestone and marble, have been measured in terms of the reaction rate between SO_2 and calcite by Gauri and Sarma (1973). The variation in reaction rate constant with SO_2 concentration for one type of marble is shown in Figure 22.



Source: Gauri and Sarma, 1973

Figure 22. Relationship Between SO_2 Concentration and the Reaction Rate for Alabama White Marble.

Spence et al. (1974) exposed four types of paints to SO_2 , NO_2 , and ozone and found SO_2 to be the primary damaging agent. Experiments were monitored in exposure chambers under controlled pollutant concentrations, temperature, and relative humidity. The combined effects of SO_2 concentration and relative humidity accounted for over 60 percent of the variability in erosion rates.

3. Particulates

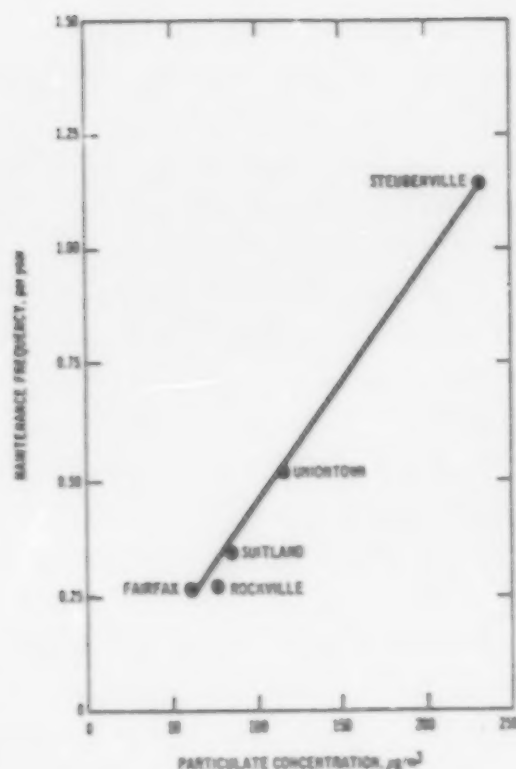
The major effects of particulate exposure on materials are the soiling and deterioration of painted and other exposed surfaces, and a number of investigations have addressed this topic (Michelson and Tourin, 1967; Booz, Allen and Hamilton, Inc., 1970; Beloin and Haynie, 1973). Degradation of painted surfaces may take the form of chalking, cracking, erosion, flaking, or changes in the color or tensile strength of paint films. Particulates have also been held responsible for

affecting the operation of electrical contacts and for causing electric flashover from insulators on high tension wires (Campbell, 1972; Robinson, 1972; Baker, 1975).

The frequency of maintenance of painted surfaces exposed to particulates has been investigated in Philadelphia (Booz, Allen and Hamilton, Inc., 1970) and in five other towns and suburbs (Michelson and Tourin, 1967). The results of the two studies are in sharp disagreement, because responses in the five cities record substantial increase in maintenance frequency with particulate concentration (see Figure 23), whereas the Philadelphia study found no significant differences (Table 16). One reason for the discrepancy may be the covariation of income and attitude towards maintenance with air pollution levels in the Philadelphia study.

The relationship between particulate concentration and rate of soiling for painted surfaces as well as cedar siding, asphalt shingles, concrete blocks, limestone, brick, and window glass was investigated by Beloin and Haynie (1973) at five test sites in Birmingham, Alabama. The materials were exposed to ambient suspended particulates at levels between 60-260 $\mu\text{g}/\text{m}^3$ over a two-year period. Soiling was expressed in terms of reflectance measurements for opaque surfaces and in terms of haze measurements for glass. The degree of soiling of painted cedar siding was found to be proportional to the square root of the particulate exposure (see Figure 24), whereas the degree of soiling for shingle siding was directly proportional to the exposure. However, the soiling of limestone, concrete, brick, and glass surfaces exhibited no clear correlation with particulate exposure.

Particulates have been found to affect the operations of electrical contacts, components, and insulators by forming a surface film (Campbell, 1972). The rate of formation on brass contacts depends strongly on both particulate concentration and relative humidity, whereas silver contacts are not significantly affected. Most of these investigations have not produced quantitative relationships that are worthy of reporting here (Robinson, 1972; Baker, 1975).



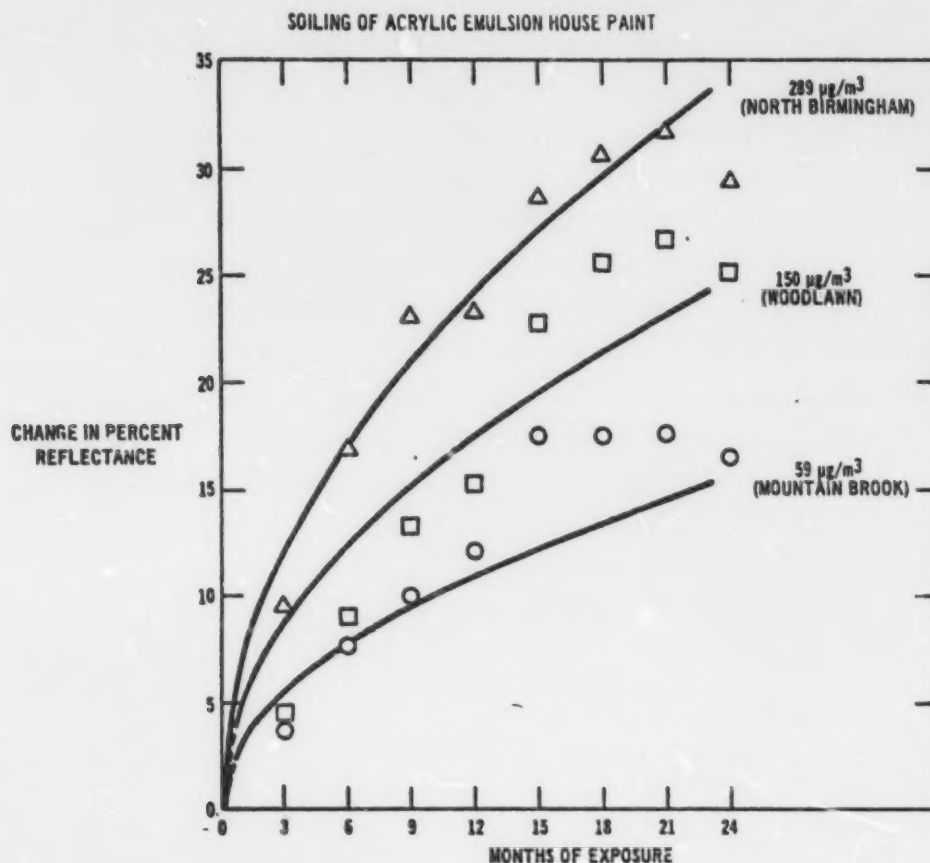
Source: Michelson and Tourin, 1967

Figure 23. Relationship Between Exterior Repainting Frequency and Particulate Concentration.

Table 16. Mean Annual Frequency of Exterior Wall Painting as a Function of Particulate Concentration in the Philadelphia Area.

Particulate concentration ranges, $\mu\text{g}/\text{m}^3$	Exterior wall painting	
	Mean annual frequency	Standard error of mean
< 75	0.28	0.018
75 to 100	0.35	0.053
100 to 125	0.35	0.041
> 125	0.29	-0.055

Source: Booz Allen and Hamilton, Inc., 1970



Source: Beloin and Haynie, 1973

Figure 24. Relationship Between Particulate Concentration, Exposure Time, and Soiling of House Paint.

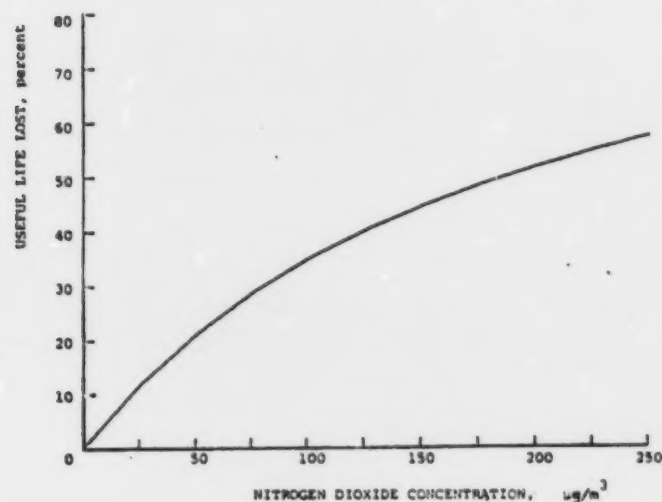
4. Oxidants and Nitrogen Oxides

Ozone damage to materials has taken the form of premature fading of fabric dyes (Salvin, 1972), and increased erosion rate of paint (Spence, et al., 1974). Ozone has also been found to act antagonistically toward sulfur dioxide in the corrosion of steel, thus decreasing the corrosion rate (see Figure 17). Nitrogen dioxide has to date been linked mainly with dye fading in fabrics (Salvin, 1972). However, a quantitative relationship was not established.

In the previously mentioned study of paints in a controlled chamber, Spence et al. (1974) found that acrylic coil coating was significantly affected only by ozone. Upon exposure to low levels of SO_2 and NO_2 and high relative humidity, the erosion rate increased from $0.735 \mu\text{m}/\text{yr.}$ at $157 \mu\text{g}/\text{m}^3$ O_3 level to $1.150 \mu\text{m}/\text{yr.}$ at the $980 \mu\text{g}/\text{m}^3$ level. This increase is, however, only slightly larger than the standard error.

In another test chamber study, red and blue cellulosic fabrics were exposed to SO_2 , O_3 , and NO_2 to assess color fading (Upham et al., 1974). NO_2 was found to contribute to fading and loss of useful fabric life both directly and in synergism with relative humidity. At 60 percent relative humidity and 25°C , the simplified dose-effect relationship is plotted in Figure 25 and expressed by the equation:

$$\text{Percentage of Useful Life Lost} = \frac{0.525 \text{ NO}_2}{1 + 0.00525 \text{ NO}_2}$$



Source: Upham et al., 1974

Figure 25. Relationship Between NO_2 Concentration and Fading of Plum Fabric.

D. OTHER EFFECTS OF AIR POLLUTION

Air pollutants affect a number of other target areas beyond human health, vegetation, and materials. The more important among these are aesthetic and meteorological effects. Quantitative relationships for these areas are very scarce because of lack of sufficient interest and/or the difficulties of measuring the effects.

1. Aesthetic Effects

Aesthetic effects may take the form of reduced visibility or odors. All of the major pollutants, with the possible exception of carbon monoxide, can contribute to the first problem and a host of minor pollutants, including ammonia, hydrogen sulfide, and mercaptans, are responsible for the second. The relationships between pollutant levels and visibility are relatively straightforward. Charlson (1969) derived a rather simple equation relating visibility to aerosol levels, which yielded a correlation coefficient of 0.82 for 238 readings in a variety of locations. Odor measurement as a function of pollutant concentration is a much more formidable problem, because the effect is largely psychic, and thus, difficult to measure.

Aesthetic effects have been usually measured in monetary terms by assessing the people's willingness to pay for pollutant abatement leading to a reduction of the offensive condition. This may be accomplished through public opinion surveys, or through studies of changes in property values as a function of air pollution levels. For example, Mason (1972) and Vars and Sorenson (1972) surveyed the opinion of tourists on heavy smoke problems in the Willamette Valley in Oregon caused by the burning of grasses. Randall et al. (1974) carried out a series of so-called bidding games designed to assess willingness to pay for abatement of particulate emissions among several population subgroups in the Four Corners area in the Southwest.

2. Meteorological Effects

Air pollution has been held accountable for changes in precipitation patterns and in the mean temperature of the earth's atmosphere. Air

pollutants also contribute to contamination of water and soil through deposition by gravity or by precipitation.

Air pollutants have been found to cause either increases or decreases in precipitation, depending on local meteorological and topographic conditions (Hersey, 1970). Unfortunately, the data base is too small for a suitable dose-effect function.

Mitchell has traced the relationship between atmospheric dust level, contributed principally by volcanic eruptions, and the drop in the mean temperature of the earth's atmosphere. This has potentially great importance, because a 1.6 percent decrease in the amount of solar radiation reaching the earth has been estimated to be capable of producing severe glaciation (Davis, 1971). However, Mitchell's results are inconclusive, because the relationship exhibits varying magnitudes and time lags.

Investigations of the contribution of air pollutants to the contamination of surface waters and soil have been conducted on Lake St. Claire (Whelpdale, 1974), on Lake Michigan (Skibin, 1973), in the Sierra Mountains (Yoshimitsu and Patterson, 1974), and in England (Hallsworth and Adams, 1973). Here again, the results are not sufficiently consistent and well-defined to permit the development of dose-effect functions.

E. EFFECTS OF WATER POLLUTION

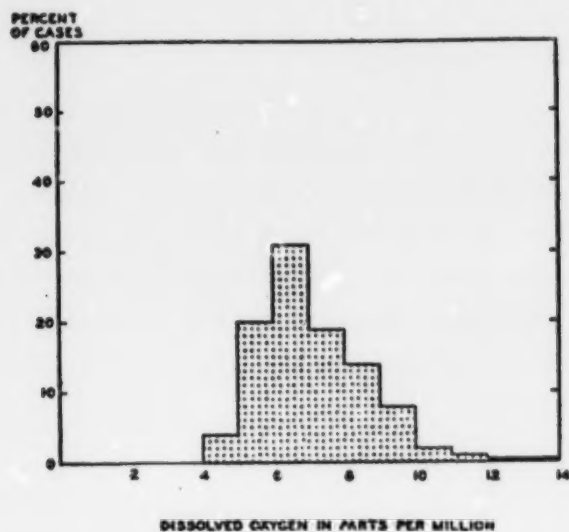
Effects of water pollution have received relatively less quantitative scrutiny than effects of air pollution, perhaps because the largest effect, loss of recreation, is so difficult to measure, and because most effects are attributable to different combinations and concentrations of various pollutants. Nevertheless, dose-effect functions have been developed for the effects of various pollutants on fish and other aquatic organisms, as well as on household plumbing fixtures.

1. Effects on Fish

Dose-effect functions involving fish and other aquatic organisms have been developed for dissolved oxygen and industrial chemicals (Ellis, 1937), acidity (Lackey, 1939), dissolved solids (Baldwin and Saalfeld, 1962; Beeton, 1965), suspended solids (Dow Chemical Company, 1968), and Kraft mill effluent (Stoevener et al., 1972).

The quantitative relationship between dissolved oxygen (DO) concentration and a desirable mix of fish species has been investigated by Ellis (1937), who found the optimum level to be between 6 and 7 ppm (see Figure 26). A desirable mix was defined as including trout, bass, sunfish, perch, suckers, buffalo, and catfish in good condition at the time of sampling. Ellis also investigated survival rates of goldfish in varying concentrations of several types of industrial waste. The results for sulphur and selenium compounds are shown in Table 17.

Ellis's findings of an optimum DO level for aquatic organisms were confirmed by Lackey (1939) who investigated the relationship between dissolved oxygen and the diversity of benthic organisms in the Shenandoah River (see Table 18). These organisms form an important element of the fish food chain and these results could be responsible for Ellis's findings. Lackey also found that the number of plankton species increased from 10 to 23 when the pH range was raised from 1.8-3.9 to 4.8-7.2.



Source: Ellis, 1937

Figure 26. Relationship Between DO Level and Percent of Cases with Desirable Fish Mix.

Table 17. Survival of Goldfish in Solutions of Sulphur and Selenium Compounds

Substance	Parts per million	pH	Survival Time
Ammonium sulfide	1,000	7.9	15 - 90 minutes
	100	7.8	72 hours - > 4 days
	10	7.7	> 4 days
	1	7.7	> 4 days
Hydrogen sulfide	1,000	6.5	45 - 60 minutes
	100	7.3	3 - 4 hours
	10	7.6	> 96 hours
	1	7.7	> 4 days
Sodium Sulfite	1,000	7.6	3 - 72 hours
	100	7.6	> 96 hours
	10	7.6	> 4 days
	1	7.8	> 4 days
Sodium selenite	1,000	7.4	60 - 130 minutes
	100	7.7	8 - 19.5 hours
	10	7.3	98 - 144 hours

Source: Based on Ellis, 1937

Table 13. Relationship Between Dissolved Oxygen Level and the Number and Weight of Benthic Organisms

DO (ppm)	No. of Benthic Organisms	Weight of Benthic Organisms
6.0	912	6.5
3.9	108	0.4
8.4	528	4.1

Source: Lackey, 1939

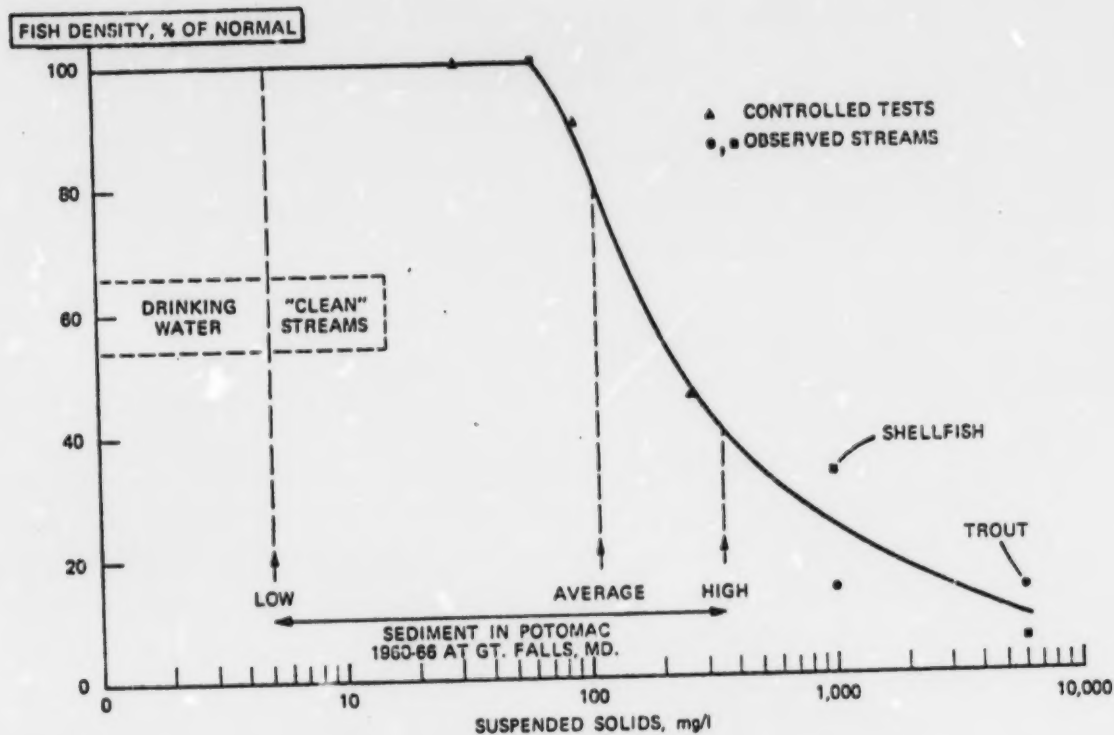
Several investigators have attempted to correlate concentrations of dissolved solids with fish productivity in the Great Lakes on the basis of records dating back to the beginning of this century (Baldwin and Saalfeld, 1962; Beeton, 1965). The fish were lake herring, blue pike, and yellow perch, whereas the dissolved solids included sodium, potassium, calcium, chloride, and sulfate. Although some negative correlation can be noted in the overall trend, the relationship is not at all consistent.

On the other hand, fish density in the Potomac River has been found to be strongly dependent on the concentration of suspended solids (Dow Chemical Company, 1968). The results are displayed in Figure 27, which shows that fish density falls to ten percent of the normal volume at a concentration of 6000mg/l. Trout and shellfish were the primary species affected.

In a related study in the Potomac River, the Great Lakes, and Yaquina Bay, fish densities have been related to concentrations of both suspended solids and Kraft mill effluents (Stoevener *et al.*, 1972). Specifically, the effects of exposure to Kraft mill effluent on flounder in Yaquina Bay are shown in Figure 28.

2. Other Effects

Other effects of water pollutants may take the form of loss of recreation and aesthetic enjoyment, damage to health and materials, and the additional expense of treating municipal, industrial, and agricultural

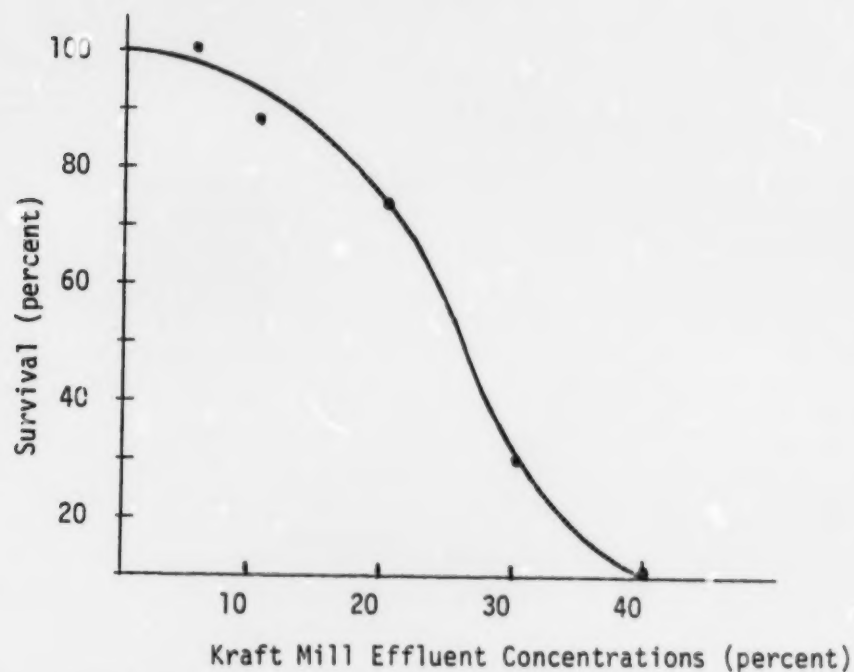


Source: Dow Chemical Co., 1968

Figure 27. Relationship Between Suspended Solids and Trout and Shellfish Density.

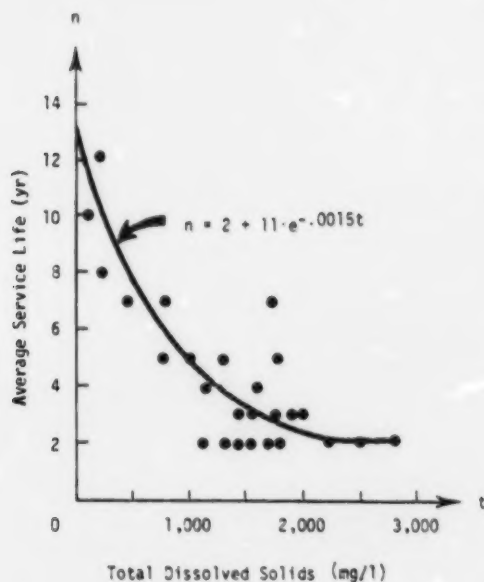
water supplies. Few of these relationships have been investigated sufficiently to permit the development of a dose-effect function, partly because the pollutants act in varying combinations and concentrations and partly because the effects are difficult to measure.

One such function was formulated by Tihansky (1974) linking total dissolved solids concentration with the life expectancy of household plumbing fixtures. The results for toilets are displayed in Figure 29.



Source: Based on Stoevener, 1972

Figure 28. Survival of Starry Flounder After 48 Hours in Various Concentrations of KME.



Source: Tihansky, 1974

Figure 29. Relationship Between Dissolved Solids and Life Expectancy of Toilets.

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III. ANALYTICAL METHODOLOGY

In spite of the potential importance of dose-effect functions and the amount of effort that has gone into generating the necessary data, the methodology for developing these functions and handling of the attendant problems and uncertainties are still in their infancy. This chapter presents the first comprehensive and systematic exposition of this subject by tracing the methodology through the progressive stages of study design, measurement of ambient levels, determination of exposure, determination of effect, estimation of functional relationships, and presentation of results.

A. DESIGN OF STUDY

Design of the study is a crucial stage in the dose-effect development process, for it sets the pattern for much of the subsequent effort and determines the usefulness of the results. The major decisions involve selection of study parameters and type of study (epidemiological or field, clinical, and toxicological or laboratory).

1. Selection of Study Parameters

The principal parameters to be selected in the design of a dose-effect study are:

- Pollutants and measures
- Effects and measures
- Population at risk
- Time frame and geographic coverage

The selection of these parameters is generally dictated by the intended use of the study, availability of data, and amount of funding, but specific parameters are subject to additional considerations. For example, the important considerations in selecting a pollutant for study may be listed as follows:

- Synergistic or antagonistic interactions
- Meteorological conditions
- Type and unit of measure
- Observation interval

Consideration of potential synergistic and antagonistic interactions of the pollutant under study with other species that may be present and the impact of certain meteorological conditions are likely to determine the type and amount of data to be collected. Decision on type of measure (e.g., mean, median, peaks, excesses), units (e.g., micrograms per cubic meter of air, parts per million), and observation intervals (e.g., hourly, daily, monthly, annual) is governed both by availability of data and by the desired precision and level of aggregation of the results.

Characterization of the population at risk, i.e., the human, vegetative, or material population exposed to pollutants under study, helps to determine its potential susceptibility to various levels of air pollution. Consequently, it is useful in defining more precisely the effects associated with a given exposure. Characterization of population at risk can also provide useful indications for allocation of resources and setting of priorities in air pollution abatement. For example, a higher clean-up priority could be assigned to an area containing a large population of older people or those exposed to high occupational pollution than to another area with a smaller population of relatively healthy people, not otherwise exposed to harmful pollutants. Such decision process can be refined further through control of specific pollutants.

Human susceptibility and resultant response to toxicological and physical stress produced by air pollutants is defined in accordance with certain intrinsic traits, such as age, race, sex, and general health, as well as by such extrinsic characteristics, as employment, income, educational level, and general environmental conditions. The age subpopulations that are considered particularly susceptible to observable effects are the very young (under 20) and the old (over 65). Genetic makeup, most readily defined along racial lines, is another predeterminant of susceptibility. Sex, a third determinant, is seldom considered, because it is distributed fairly evenly in most community studies.

The type or place of employment is an important indicator of exposure to industrial air pollution, and the subpopulation engaged in manufacturing should be identified as a minimum. Educational level relates to an awareness of the need for proper nutrition, health care, and protection from air pollutants. Finally, family income again correlates with the nutritional and health care levels, but may also serve as an indicator of the willingness to pay for abatement of air pollution in economic studies. Although these intrinsic and extrinsic traits and characteristics are not considered etiological agents of disease, studies of their correlation with health effects have been helpful in isolating the likely agents, such as specific air pollutants, and in shaping social policy. (Takacs and Shea, 1975).

2. Epidemiological, Field, and Clinical Studies

Epidemiological studies are by far the most common approach to the assessment of health effects of air pollutants. These studies involve collection of available air quality and health effects data and measurement of their relationship and degree of correlation. Clinical observations of individuals who come under medical or clinical attention represent a rather limited source of health effect information. Field observations apply to assessment of air pollution effects on vegetation and materials. In most other respects, these two approaches are rather similar to epidemiological studies.

In the performance of epidemiological studies, the investigator can select to a large extent, but not control, composition of the air, extent of exposure, population at risk, and type of effects sought. Whenever feasible, he should take into account synergistic interactions among pollutants, influence of such cofactors as humidity, temperature, occupational exposure, and smoking habits, as well as the role of population characteristics, including age, sex, race, and state of health, in producing the observed effects. Accounting for meteorological factors is particularly important in the case of field studies,

because wind, precipitation, humidity, and related factors play a major role in conveying pollutants to the plant and material subjects and in the damage mechanism.

Epidemiological studies may be longitudinal or cross-sectional. The former are more common and compare exposure and effects for a selected population in the same location over a period of time. Cross-sectional studies deal with similar population groups in different locations during the same period of time. These studies are more susceptible to misleading interference from extraneous factors that are more likely to vary with location than with time.

Epidemiological studies may also be classified as retrospective or prospective. Retrospective studies can be accomplished more quickly and are thus more common, but they force the investigator to make do with frequently inadequate available historic data. Prospective studies, on the other hand, involve future observations and afford the investigators some control over data collection procedures and format, but accumulation of the necessary data may take a number of years.

The great advantage of epidemiological and field studies over other approaches to assessment of the effects of air pollutants is the large number of available observations of both air quality and effects. This permits the identification of massive trends which are not as affected by random errors of observation and differences in population characteristics. The major drawback is the lack of effective control over the type, quality, and format of the data.

Clinical observations have the advantage of intensive, expert evaluation of health effects, but the data may not be readily accessible because of confidentiality, fragmented storage, and difficulty of retrieval. Moreover, the inherent selection of a population with clinical symptoms biases the sample toward the more susceptible groups and denies information on negative effects. This approach is most suitable for investigating the effects of occupational or other highly localized exposure.

Finally, it should be noted that epidemiological and field studies and clinical observations can only show an association between exposure to pollution and the observed effect, suggesting the existence of a causative relationship. Such a relationship can then be tested by toxicological or laboratory studies. It can be rendered plausible by the presentation of a reasonable connective mechanism, or other weight or reason.

3. Toxicological and Controlled Experiments

Toxicological investigations involve deliberate administration of controlled doses of specific pollutants to animal, and occasionally human, subjects and observation of the resulting effects. Other controlled experiments represent essentially the same approach for determining effects of pollutants on plants and materials. In all cases, the investigator can control the type and concentration of pollutant, exposure time and rate, composition of the population at risk, and the procedure for observing and recording effects.

Thus, in a typical toxicological experiment, selected inbred animals of uniform strain, weight, age, and sex are exposed to controlled amounts of pollutant for specified periods of time, and the resulting effects are noted and recorded. The experiment is repeated a number of times, with new populations and different exposures, until a definite relationship, or lack thereof, has been established. Toxicological experiments on human subjects are socially unacceptable in most instances, with the possible exception of low doses of the less harmful pollutants, such as carbon monoxide, photochemical oxidants, and sulfur dioxide, because of the relative mildness and reversibility of their effects.

A similar procedure applies in other controlled experiments involving plants and materials. Controlled experiments on the effects of oxidants and other air pollutants on plant growth and yield have been conducted in the field in side-by-side exposure chambers supplied, respectively with monitored ambient and filtered air. The more recent

chambers are open at the top to admit rainfall and thus reproduce more closely natural conditions. Other investigators have assessed the effects of oxidants by spraying alternate crop rows with fungicides which protect the plants from ozone.

Because all conditions of the experiments can be strictly controlled, toxicological and other similar investigations are uniquely suited to prove the existence or lack of a causal relationship between dose and effect. In this sense, these investigations provide valuable supportive evidence to epidemiological and field studies.

On the other hand, pollution concentrations required to demonstrate these effects in the laboratory are seldom experienced in urban air, and it becomes questionable whether the results of such experiments are valid in assessing the effects of pollution exposure of the general population. Conversely, if the hypothesized effect is small, it may not be practical to test for it within the temporal constraints of a controlled experiment. Moreover, differences in physiology, life span, and dose rate make it difficult to extrapolate results from animal studies to human effects.

4. Surveys

Surveys can serve two important needs in assessing the effects of air pollutants: amplification of health effect data and reporting of less tangible effects. The typical tools of surveys are mailed questionnaires and personal interviews.

Amplification of health effect data typically involves learning about the background of a sample of people who died from a particular disease to identify implicated factors. Information of interest may include general state of health, smoking habits, and occupational exposure. In other cases, subjects of a morbidity investigation are requested to maintain diaries, where they note the occurrence and direction of any adverse symptoms. These surveys share many of the characteristics of epidemiological and field studies, except for the actual method of data collection.

Assessment of the less tangible aesthetic effects of air pollutants involves interviews to gauge changes in public opinion and behavior resulting from perception of impaired visibility, soiled surfaces, offensive odors, or smarting eyes. In addition to the common public opinion poll, some of the techniques for gauging these changes in opinion and behavior include estimation of willingness to pay for pollution reduction through the so-called bidding games and determination of losses in property values. This affords the rare opportunity of inferring a dose-effect function from an economic relationship. Unfortunately, surveys of public opinion and behavior are notoriously imprecise and provide at best only a qualitative assessment of the aesthetic effects of air pollutants. Proper education of the subject and minimal bias in the questioning can help to improve the validity of the results.

B. MEASUREMENT OF AMBIENT LEVELS

Measurement of ambient levels of pollutants, the first step in the development of a damage function, is complicated by the substantial variations of these concentrations in both space and time, diverse locations of receptors and monitoring instruments, inadequate sampling and measurement techniques, and inconsistent expression and aggregation of results. These problems are taken up here in turn, in preparation for the second step - determination of exposure, in the next section.

1. Formation of Ambient Levels

Ambient pollutant levels are governed by physical and chemical processes experienced by pollutants in the atmosphere under the influence of meteorological and topographic factors. The important considerations here are the nature of pollutant sources, the atmospheric processes, and their impact on air quality.

Pollutant emission sources may be classified on the basis of their mobility into stationary and mobile sources; on the basis of their size and shape, into point, line, and area sources; on the basis of their elevation, as ground-level or elevated sources; and on the basis of emission continuity, as continuous or intermittent sources. At times, however, some of these distinctions become blurred. Thus, emissions from a highway, normally considered a stationary line source, are actually contributed by numerous mobile point sources, and emissions from a number of home heating furnaces are typically lumped together as arising from a diffuse area source.

Upon leaving their respective sources, pollutants are subjected to a number of physical and chemical processes that are responsible for their transport, mixing, dispersion, and removal, as well as formation of secondary pollutants. The physical processes are governed both by meteorological factors, such as wind speed and direction, temperature distribution, and precipitation, and by topographic features, including mountains, valleys, and water bodies, as well as by human activities.

Temperature distribution in the atmosphere overlying the sources determines the mixing height - an effective ceiling, under which pollutants are mixed and dispersed by air turbulence. Precipitation cleanses the atmosphere by dissolving, adsorbing, or sweeping the pollutants and bringing them down to earth. The larger particles settle out on their own under the force of gravity.

Topographic features provide lateral containment or ventilation for the mixing layer. Impact of human activities on atmospheric processes is best illustrated by the so-called heat island effect. Large amounts of waste heat ejected by an urban area tend to set up a closed convection cell, in which air rises over the urban area, diverges outward in the upper layers of the atmosphere, descends over the adjacent rural areas, forming secondary pollutants, and finally converges inward in the lower atmospheric layers. In effect, the pollutants are trapped, converted, and recirculated within the metropolitan region, mixing primary pollutants from the city with secondary pollutants from the countryside.

Secondary pollutants are produced by chemical reactions in the atmosphere which are affected by temperature, humidity, and the sun's ultraviolet radiation. The more prominent reactions are the formation of photochemical oxidants by various combinations of pollutants, including nitrogen dioxide and hydrocarbons, oxidation of sulfur dioxide and nitrogen dioxide to the more hazardous nitrates and sulfates, respectively, generation of particulates by vapor condensation, and adsorption of gaseous pollutants on particulate surfaces.

2. Problems of Measurement

Attempts to relate ambient levels to pollutant emissions rely on analytical and statistical models of the various physical and chemical processes described above. Analytical models are based on a postulated and validated mathematical relationship between ambient levels and pollutant emission patterns, with meteorological and topographic factors as additional independent variables.

Statistical models, on the other hand, use historic data to relate observed ambient levels to various meteorological parameters, assuming that emission patterns remain constant. All of these models rely on certain critical assumptions about emission, meteorological, and/or topographic patterns. Their accuracy depends both on how well these assumptions hold for the situation at hand and on the availability of sufficient measurements to calibrate the model.

Because of the poor availability of historic emission data and the difficulty of applying analytical and statistical models, nearly all attempts at developing dose-effect functions have relied on measured values of ambient concentrations of specific pollutants. Such data have been collected since the late 1950's by the National Air Surveillance Network (NASN) and since 1962 by the Continuous Air Monitoring Program (CAMP). More recently, availability of air quality data has been bolstered by enactment of the Clean Air Act, which requires that each state measure and report ambient concentrations of total suspended particulates, sulfur dioxide, nitrogen dioxide, photochemical oxidants, and carbon monoxide. Both Federal and state data are supplied to the U.S. EPA National Aerometric Data Bank (NADB), where they are available for public use.

The key dilemmas in measurement of ambient levels are:

- Decision on precisely which pollutant species is to be measured
- Selection of the most appropriate analytical technique
- Location of the sampling and monitoring equipment
- Presentation of data.

The major pollutants investigated in development of the dose-effect functions reviewed in Chapter II and the corresponding studies are listed in Table 19. It will be noted that sulfur dioxide and particulates represent by far the most studied pollutants. A good illustration of the first dilemma listed above is presented by the measurement of sulfur dioxide and particulates as proxies for

Table 19. Pollutants Identified in Development of Dose-Effect Functions

Pollutant	Health Effects	Vegetation	Materials
Particulates, smoke shade, coefficient of haze, soiling index, dust	Buechley <i>et al.</i> , 1973; Glasser and Greenburg, 1971; Hagstrom <i>et al.</i> , 1967; Hodgson, 1970; Jaksch, 1973; Schimmel and Greenburg, 1972; Schimmel and Murawski, 1975; Silverman, 1973; Sterling <i>et al.</i> , 1966, 1967, 1969; Winkelstein, 1967, etc.; Zeidberg <i>et al.</i> , 1964, 1967		Beloïn and Haynie, 1973; Booz, Allen and Hamilton; Campbell, 1972; Mattson and Holm, 1968; Michelson and Tourin, 1967; Robinson, 1972
Sulfur dioxide (SO ₂), sulfates (SO ₄)	Buechley <i>et al.</i> , 1973; Durham, 1974; Finklea <i>et al.</i> , 1975; Glasser and Greenburg, 1971; Hagstrom <i>et al.</i> , 1967; Hodgson, 1970; Lave and Seskin, 1973, in press; McDonald and Schwing, 1973; Schimmel and Greenburg, 1972; Schimmel and Murawski, 1975; Sprey <i>et al.</i> , 1974; Sterling <i>et al.</i> , 1966, 1967, 1969; Winkelstein <i>et al.</i> , 1967, etc.; Zeidberg <i>et al.</i> , 1964, 1967	Bleasdale, 1973; Davis, 1972; Dochinger <i>et al.</i> , 1972; Guderian <i>et al.</i> , 1960; Hill <i>et al.</i> , 1974; Linzon, 1966; Mansfield and Bull, 1972; Menser and Heggstad, 1966; O'Gara, 1922; Stone and Skelly, 1974; Temple, 1972	Aziz and Godard, 1959; Brysson <i>et al.</i> , 1967; Gauri and Sarma, 1973; Guttman, 1968; Haynie, 1975; Haynie and Upham, 1970, 1971; Mattson and Holm, 1968; Sereida, 1960; Spence <i>et al.</i> , 1974
Nitrogen dioxide (NO ₂), nitric oxide (NO)	Chapman <i>et al.</i> , 1973; Durham, 1974; Hammer, 1974; Lave and Seskin, in press; McDonald and Schwing, 1973; Pearlman, 1971; Shy <i>et al.</i> , 1970, 1973; Sprey <i>et al.</i> , 1974; Sterling <i>et al.</i> , 1966, 1967, 1969	Hill <i>et al.</i> , 1974; Stone and Skelly, 1974; Taylor and Eaton, 1966; Thompson and Taylor, 1969; Thompson <i>et al.</i> , 1971	Salvin, 1972; Upham <i>et al.</i> , 1974
Photochemical oxidants	Durham, 1974; Hammer, 1974; Hexter and Goldsmith, 1971; Sterling <i>et al.</i> , 1966, 1967, 1969; Wayne and Wehrle, 1969	Barnes, 1972; Botkin <i>et al.</i> , 1971; Brewer and Ferry, 1974; Costonis and Sinclair, 1969; Davis and Wood, 1972; Feder, 1970, 1972; Feder <i>et al.</i> , 1972; Heagle and Heck, 1974; Heck and Tingey, 1971; Heck <i>et al.</i> , 1968; Heggstad, 1973; Linzon, 1966; Menser and Heggstad, 1966; Miller, 1973; Thompson, 1975; Thompson and Kats, 1975; Thompson and Taylor, 1969; Thompson <i>et al.</i> , 1972; Turner <i>et al.</i> , 1972	Haynie and Upham, 1971; Salvin, 1972
Carbon monoxide	Anderson <i>et al.</i> , 1973; Aronow <i>et al.</i> , 1972, 1973, 1974; Hammer, 1974; Hexter and Goldsmith, 1971; Lave and Seskin, in press; Sterling <i>et al.</i> , 1966, 1967, 1969		
Other (hydrocarbons, non-specific)	Anderson <i>et al.</i> , 1965; Ferris and Anderson, 1964; Ferris <i>et al.</i> , 1973; Lave and Seskin, in press; McDonald and Schwing, 1973	Kratky <i>et al.</i> , 1974; Likens and Borman, 1974; McCune, 1969; McCune and Weinstein, 1971; Poovaiah and Wiebe, 1973; Swedish Royal Ministry for Foreign Affairs, 1972; Thompson and Taylor, 1969; Wiebe and Poovaiah, 1973; Wood and Borman, 1974	Baker, 1975; Dunbar, 1968; Greenlee and Plock, 1968; Van Rooyen and Copeson, 1968

sulfates, or perhaps some other unsuspected pollutant, once it became evident that SO_2 alone is not a major cause of adverse health effects. Investigators have turned to a number of additional indices related to particulate concentrations, such as smoke shade, coefficient of haze (COH), and soiling index. Finklea et al. (1975) went on to develop an empirical relationship between sulfur dioxide and sulfate levels.

The remaining three dilemmas are taken up in more detail in the sections that follow.

3. Methods of Measurement

A detailed discussion of the various methods of sampling and measuring the concentration of specific air pollutants is clearly beyond the scope of this report. However, the general characterization of these methods and of the attendant problems and errors is an essential element of the methodology for developing dose-effect functions. The principal characteristics of monitoring methods are:

- Sampling frequency
- Specificity
- Accuracy and precision, or reproducibility.

A sampling can be performed in either a batch-type or a continuous mode. The first mode involves sampling the air over a predetermined period of time and is followed by an analysis of the accumulated sample. This may be illustrated by the high-volume sampler that collects particulates on a fiber filter, or the West-Gaeke-sulfamic acid technique for sulfur dioxide, which relies on bubbling air through an absorbent solution. The batch-type mode typically yields 24-hour average concentrations and obliterates diurnal variations.

The continuous sampling mode, illustrated by the chemiluminescent technique for ozone measurement, yields a continuous index of pollutant level. This output can be displayed on chart paper and digital readout units, or stored in a magnetic memory. Integration and averaging of these results over a preselected period of time can be accomplished with the aid of electronic circuitry.

Specificity and selectivity refer to the ability of a given method to measure the concentration of a particular pollutant in the presence of other, potentially interfering species. Accuracy, precision, and reproducibility reflect the proximity of replicate measurements to the true value and to one another. These considerations weigh heavily in the approval and acceptance by the U.S. EPA of the numerous measurement methods available.

The U.S. EPA has classified all air quality measurement methods into three categories: approved, unacceptable, and unapproved (neither approved nor unacceptable). At present, only the Federal Reference Methods (FRM) have been officially approved. These are described in appendices to 40 CFR Part 50, originally promulgated with the National Ambient Air Quality Standards on 30 April 1971. These appendices also introduced the concept of an "equivalent method", which provides that a method may become approved only by demonstrating equivalence to the reference method. (U.S. EPA, 1974).

The Federal Reference Methods for several pollutants are listed below:

- Total suspended particulates -- High volume sampler is the only acceptable method
- Sulfur dioxide -- The manual West-Gaeke-sulfamic acid (24-hour bubbler) method is the Federal Reference Method and other manual methods are unacceptable; continuous methods are unapproved
- Nitrogen dioxide -- The manual NASN bubbler method is considered unacceptable; all other methods are unapproved
- Photochemical oxidants (ozone) -- Continuous chemiluminescent method is the Federal Reference Method specific for ozone; a number of other methods for total oxidants are designated unacceptable
- Carbon monoxide -- The non-dispersive infrared (NDIR) is the Federal Reference Method; other methods are unapproved
- Total hydrocarbons (corrected for methane) -- Gas chromatographic flame ionization is the Federal Reference Method.

It should be noted that there are presently no acceptable techniques for measuring the very important pollutants nitrogen dioxide, nitrates, and sulfates, and indirect techniques subject to large errors and uncertainties must be used. In the case of a number of other pollutants, past techniques have been modified or altogether replaced, destroying the continuity of historic air quality records.

Errors in measurement of air quality are associated with both sampling procedures and analytical techniques. In the first instance, errors arise from inadequate control of the volume of air sample through malfunctions of pumps, flow meters, or other flow regulating devices, as well as from non-uniform retention in the filter or fluid. Error in analytic techniques can be attributed to human error, as well as to malfunctions of the analytic equipment.

4. Location of Monitoring Equipment

Adequate representation of ambient air quality requires both a sufficient number of monitoring stations and their judicious placement in the area under investigation. The first requirement is subject to budgetary constraints on the capital outlay for equipment and the costs of operation and data handling. Both tasks are necessitated and considerably complicated by the heterogeneity of the pollutant concentration field engendered by non-uniform emission patterns and atmospheric processes.

Studies of air pollution health effects revolve around available air quality data, but no metropolitan area systematically monitors all of the air pollutants alleged to affect health. Consequently, attribution of important health effects to certain air pollutants may well have been missed. As a case in point, recent investigations of the chronic health effects of nitrogen dioxide indicate that the national standard, established on the basis of very scant evidence, is substantially too high. (Sprey and Takacs, 1973).

Lack of sufficient monitoring stations is a very serious problem that has plagued nearly every investigation of effects of air pollutants. In urban areas, it has meant inadequate representation of exposure

for the population at risk. The virtual absence of monitoring stations in rural areas has frustrated attempts to assess crop damage from recently discovered high levels of photochemical oxidants.

Common criteria for siting monitoring equipment are:

- Population density
- Absence of nearby or upwind pollution sources
- Accessibility, logistics, and security.

The first criterion calls for placement in the midst of the highest population density in an effort to reflect the ambient quality experienced by the greatest number of receptors. One major flaw here is that people are highly mobile. Another is that some pollution sources (e.g., automobiles or space heating) effectively move with people on a diurnal basis. Finally, this criterion cannot apply to secondary pollutants (e.g., photochemical oxidants, sulfates, and nitrates) which are formed through atmospheric processes, often at large distances from both the high population densities and the associated sources of primary pollutants.

The second criterion, concerned with improving representation of the measured values for the largest geographic area, calls for placement of the monitoring station away from automobile exhausts and stacks of power or industrial plants. This criterion is frequently in conflict with the first one, in as much as emission sources tend to coincide with high population densities, especially in the case of automobile exhausts.

Accessibility, logistics, and security usually turn out to be the most operative criteria, for obvious practical reasons. Typically, this implies a rooftop location, equipped with an elevator, sufficient electric power, and a lockable enclosure. Here again, the sensors are considerably removed from the great mass of receptors at street level.

In light of these conflicts, location of a monitoring station invariably represents a compromise, where some virtues are given up for the sake of others. Physical remoteness between sensors and receptors looms as the largest problem. On the other hand, recognition of a

mistaken location does not solve the problem either, because moving the monitoring equipment to a more optimal location often involves the greater evil of losing continuity of historic air quality records.

5. Presentation of Data

Presentation of ambient air quality data involves a three-fold concern for data retrieval, aggregation, and display. Data retrieval is very much governed by the state of technology and budgetary constraints. State of aggregation is dictated in part by the nature of sampling equipment and by the intended use of the results. Display format should be guided only by the intended use of the results.

Until recently, monitoring data have been recorded by hand, or on strip chart devices, and considerable effort has been required to transfer such information to computer records. Automated systems now in use in some locations are capable of transmitting data directly to a central data acquisition and storage facility. The manual labor required to analyze chemically many samples and to review and verify recorded data has been so extensive that there exists a considerable backlog of inaccessible data, particularly in Federal programs. For example, detailed summaries of the National Aerometric Surveillance Network (NASN) observations reported by station are only available through the year 1968. The recent implementation of the Storage and Retrieval of Aerometric Data (SAROAD) dissemination programs by U.S. EPA is expected to improve this situation.

Because of the many problems in station operation and maintenance, existing data are often intermittent and of questionable accuracy. Over the years, comparatively little effort has been devoted to quality assurance of data and to the determination of equivalency for methods where methodology has been changed or equipment upgraded. The degree of uniformity in Continuous Air Monitoring Program (CAMP) data has been checked from time to time and the quality control of data from the California Air Resources systems is well documented. However, less than half of the present data available in the National Aerometric Data Bank (NADB) are considered valid on a national basis.

Aggregation of air quality results can be carried out on both a temporal and a spatial basis. In the first instance, the common units, beyond instantaneous or continuous readings, are hourly, daily, monthly, and annual averages, as well as the frequency or length of time that the measured values exceeded a given level, such as air quality standards. Assessments of acute effects associated with short exposures rely on hourly or daily averages, as well as on 90th or 99th percentiles of the daily averages, or on the frequency of violation of the short-term standard, over a period of one year. Chronic effects are more likely to relate to monthly or annual arithmetic or geometric means, or the length of time during which the long-term standard has been exceeded. Spatial aggregation of air quality data may take place over a city, county, or SMSA, over a region, such as an air quality control region, over a state, or over the entire country. Certain combinations of temporal and spatial aggregations are not very practical (e.g., state hourly averages or national daily averages).

Air quality data, as most other measurements, may be displayed numerically and graphically. Most gaseous concentrations are reported in micrograms per cubic meter of air ($\mu\text{g}/\text{m}^3$), or in volume parts per million (ppm), but other units have been adopted to suit specific needs. For example, settleable particulates may be measured in a dust fall jar as mass per unit area and time. Expression of pollutant levels as a fraction of the corresponding national air quality standard has been found useful by some investigators. Graphic representation of a pollutant concentration field over an area may take the form of equal concentration isopleths for a given set of meteorological conditions. Probability of occurrence of certain pollutant concentrations over a given area may be presented in the form of a "pollution rose" indicating frequencies of occurrence of various pollution levels.

C. DETERMINATION OF EXPOSURE

The exposure to air pollutants, which is responsible for the observed effects in a dose-effect study, is closely related to the ambient pollutant levels discussed in the preceding section. Here we take up the problems associated with this translation of ambient level into a measure of exposure. The material is presented under the headings of dose and dosage, mobility, shielding, and uptake, and measures of exposure.

1. Dose and Dosage

Exposure is typically measured as some formulation of ambient concentration levels and their duration, which may be expressed as a "dosage" or "dose". Dosage is the integral of the time and ambient concentration to which the subject has been exposed, while dose represents that fraction of the dosage that has been instrumental in producing the observed effect. In the case of health effects, this is the amount actually inhaled and retained, whereas for plants and materials it is the portion that comes into actual contact with the susceptible surfaces. The direct measurement of dose is neither practical nor necessarily desirable for most applications, as long as the same analog of dose, such as average or peak concentration and dosage, is used both in the formulation and interpretation of dose-effect functions.

An important concept in the determination of exposure is the dose rate, or the variation of concentration level with time. Acute effects and those characterized by a definite threshold level are produced when ambient concentration exceeds a certain level. In these cases, one is concerned primarily with the length of time during which ambient concentration exceeded that level. On the other hand, chronic and cumulative effects are likely to result from exposure at all concentrations, and here dosage is the more appropriate measure.

The commonly measured gross dosage is the integral of concentration and time recorded at the monitoring station. The difference between this quantity and dose may be accounted for by several important factors:

- Non-uniformity of the pollution field
- Mobility of subjects
- Shielding of subjects
- Uptake characteristics.

The first of these is concerned with likely differences in concentration between location of the sampling instrument and the subjects. The second factor refers to the daily commuting, weekend and vacation travel, and long-term migrations of the human population. The third factor deals with differences in ambient concentrations between the outdoors, where monitoring stations are located, and the indoors, where the building enclosure provides some shielding for the human population. Finally, uptake characteristics determine how efficiently the ambient concentration affects the subject.

Non-uniformity of the pollution field was taken up in the preceding section. The other factors are discussed below.

2. Mobility, Shielding, and Uptake

Exposure of stationary subjects, i.e., plants and most materials, is determined by the dynamics of the pollution field alone. However, for humans, animals, and other moving subjects, exposure is governed both by motion of the pollution field and by their own mobility. Human mobility takes the form of daily commuting and shopping trips between residential neighborhoods, commercial and industrial areas, and shopping centers, weekend and vacation travel to the less polluted countryside, and migrations to regions of the country promising greater opportunity.

Studies of air pollution health effects have frequently ignored the issue of human mobility, because there is no expedient way to assess its influence. Instead, it is frequently assumed that short-term mobility will help average out the non-uniformities in the pollution field, and that long-term mobilities are not too different among the various populations under study. The Federal Highway Administration has data on traffic zones between places of residence and employment for some 123 SMSAs which could provide some insight into this issue.

The need to consider the effect of shielding by building enclosures on exposure is underlined by the fact that an overwhelming portion of the U.S. population spends some 85 percent of its life indoors. This is especially true in the more polluted urban areas, although there is no information on the frequency distribution. Actually, indoor atmospheres may be more polluted in some respects, particularly in manufacturing and processing plants and in residences with faulty heating equipment.

The effects of various building enclosures on air quality have been investigated by Yocom et al. (1971) and Wade et al. (1974). Their salient conclusions were as follows:

- Indoor concentrations of particulates vary from 20 percent of outdoor concentration for public buildings in the winter to nearly 100 percent for private homes in the summer
- Large particles and the more reactive pollutants, such as SO₂, NO₂, and ozone are probably fairly well removed by building enclosures
- Carbon monoxide readily penetrates all structures
- Gas stoves contribute NO₂, NO, and CO emissions and raise indoor concentrations above those of the outdoors.

Uptake of air pollutants by humans and animals, on one hand, and plants and materials, on the other, exhibits important differences. The former, sometimes termed "active" receptors, bring pollutants in contact with the susceptible surfaces through inhalation and swallowing of the pollutant-laden mucus. Here the rate of uptake is a function of breathing rate, lung capacity, and nasal and ciliar defense mechanisms, and it remains fairly constant for an individual at a given level of activity.

Conversely, plants and stationary material objects are dubbed "passive" receptors, because pollutants are brought up and removed by external meteorological factors, such as wind and air, while humidity and temperature play a major role in the attack mechanism.

In this case, the rate of uptake depends not only on these meteorological conditions, but also on the attitude and texture of the susceptible surface and the presence of any protective mechanism, such as a vapor barrier formed by evapotranspiration from a leaf's surface.

3. Measures of Exposure

The three measures of exposure are various forms of concentration, dosage, and dose and their applicability depends on the type of pollutant and effect under investigation. In actual practice, several different measures may be tried and the one exhibiting the best correlation with the effects sought is selected. Moreover, it may be useful to construct composite indices, made up of several measures of exposure, that would yield an even better correlation.

The simplest measures, of course, are average concentration during a given period of time, or conversely, time at a given level of concentration. These are used typically in controlled experiments, where concentrations do not vary substantially.

The frequency, duration, and/or intensity of peaks or instances when ambient concentration exceeds a certain level are useful measures of exposure in conjunction with acute effects or effects characterized by a threshold value. An example of the latter is smarting of the eyes induced when the concentration of photochemical oxidants rises above a certain level.

Dosage, or the integral of concentration and time, on the other hand, is more applicable to cumulative pollutants, such as particulates or heavy metals, and to chronic effects, or ones characterized by a ceiling value. An example of the latter effect is the soiling of an exposed surface, the appearance of which does not deteriorate significantly, once an initial layer of crud has been deposited.

Direct measurements of dose are useful in explaining an attack mechanism and in documenting a causal relationship between exposure and effect. However, their use as a measure of exposure is neither practical nor desirable. Dose measurements do not lend themselves to massive studies, because they rely on examination of individual

characteristics, and they are not readily translated into acceptable ambient levels, which is a common purpose of dose-effect studies. Thus, the relationship between dose and the actual measure of exposure selected for the study becomes implicit in the ensuing damage function.

The feasibility of conducting direct measurements of dose necessarily varies with pollutant and type of investigation. In toxicological experiments, dose can be measured by analysis of tissues of sacrificed animals, provided that the pollutant or its metabolites persist for a sufficiently long time and can be distinguished from other substances present. In human experiments, such measurements can be made for carbon monoxide by measuring the carboxyhemoglobin content in the blood, and for low doses of other pollutants, by comparative analysis of inhaled and exhaled air. In some cases, measurements are feasible with the aid of a radioactive label or other type of tracer mixed with the pollutant, or administered separately, if it shares the uptake characteristics of the pollutant.

In the case of plants and materials, particulate doses can be measured in terms of the total weight and size distribution of the deposited particles, although only a small fraction of these is likely to react with the surface before being blown off by the wind or washed off by the rain. The amount actually taking part in the attack can be measured by analyzing the plant tissues or the composition of the reacted surface layer of the material.

D. DETERMINATION OF EFFECT

Having discussed measurement of ambient levels and exposure, the independent variables of damage functions, we are now ready to tackle the dependent variable, i.e., the associated effect. Subsequent sections will address establishment of functional relationships and presentation of results. The presentation here comprises an introduction, followed by an examination of the effects of air pollution on health, vegetation, and materials.

1. Definitions

Precise definition of the effect under study is perhaps the most important requirement in the successful development of a damage function. Such a definition revolves around the following attributes:

- Type of effect
- Duration
- Reversibility
- Sensitivity
- Specificity
- Threshold and saturation
- Measures.

These are now discussed in turn.

Terms commonly used to denote effect include response, injury, and damage. The first of these implies a change in the activity of the subject and is thus not applicable to the numerous situations where the subject is inanimate. Injury is a more general and applicable term for observable effect. Finally, damage is injury of such type and magnitude that it affects the normal function of the subject. The definition of damage also includes functional aggravation of a preexisting injury and predisposition to future damages.

For example, initial injury to the surface of a leaf or the paint coat of a steel girder is generally not regarded as a damage, unless and until it threatens the strength of the latter and the metabolic

function of the former. However, the same injury would be considered damaging, if the paint served an additional aesthetic function and the leaf were used as cigar wrapper stock.

Duration of damages provides for their classification as chronic or acute. The former typically result from long-term exposure to low concentrations of pollutants, are characterized by extended duration of development, delayed detection, and long prevalence, and may be illustrated by most forms of cancer. Because of these characteristics, development of damage functions involving chronic effects is very difficult. Acute effects, usually associated with short-term exposure to high pollutant levels, are characterized by very rapid development and detection and rather brief and dramatic effects, such as the "excess" deaths registered during a severe air pollution "episode". It should be noted, however, that long-term, low-level exposure is also likely to provide a predisposition to acute effects, and conversely, one or more short-term high-level exposures could eventually produce chronic effects.

A related aspect of biological damages is reversibility, i.e., the ability of the subject to repair the damage and restore the function, upon cessation of exposure. A good example of reversible damage is low-level intoxication with carbon monoxide. On the other hand, exposure to even low levels of certain heavy metals leads to their accumulation in the body organs, and eventually, irreversible damage.

The type and severity of effects resulting from a given exposure to a specific pollutant are governed in large measure by the sensitivity and susceptibility of individual members or classes of the population. The distinction drawn here between susceptibility and sensitivity is somewhat arbitrary, but useful. Members of a given species, such as Homo sapiens, tend to have a similar sensitivity to the effects of air pollution, in the sense that their tissues are likely to experience a similar effect, upon a given exposure to a specific pollutant. However, the very young, the very old, and people afflicted with other disorders are more susceptible to observable damage, such as illness or death. Various plant species, on the other hand, differ in sensitivity

to air pollutants and may be bred with this trait in mind. In such a case, the cost of breeding the resistant variety and any associated loss in productivity must be included in the calculation of total economic damage.

In assessing specific effects of a given level of exposure, it is very important to isolate the influence of any cofactors and mimics. The former are factors that act simultaneously, synergistically, or antagonistically with the pollutants. This may be illustrated by the dramatic influence of moisture in the corrosive effects of sulfur dioxide on metals. On the other hand, photochemical oxidants appear to act antagonistically toward sulfur dioxide, perhaps by forming a protective metal oxide film. Mimics are factors that simulate the effect of certain pollutants. A classic example is that presented by ozone and nuclear radiation, both of which cause disruption of chromosomes. Because of their large variety and importance, cofactors and mimics will be taken up in greater detail under the individual target areas below.

The concept of exposure threshold has been the subject of considerable and heated debate in connection with establishment of air quality standards. This concept holds that, for every specific combination of pollutant, cofactors, effect, and population at risk, there exists an initial level of exposure up to the threshold value, which is not associated with significant, or at least, observed damage. Conversely, one can also postulate a saturation level of exposure, resulting in extreme effects (e.g., destruction of the target population), such that additional exposure does not result in additional observed damage.

The common practice of setting air quality standards at, or just below the corresponding threshold levels has engendered considerable controversy, which revolves around the various possible interpretations of the threshold concept. Since threshold levels are largely contingent on the ability to observe and measure small degrees of damage in large populations, they become continually eroded with improving state of the art in damage assessment. Moreover, it is known that low levels of certain pollutants which are incapable of producing measurable damages,

nevertheless generate a predisposition to subsequent damage. Thus, the proponents of reduced standards advocate that these be set at 1-3 orders of magnitude below threshold levels, depending on the gravity of the corresponding damage, to ensure public safety. Opponents argue that the economic costs and other deprivations associated with controls required to achieve such low standards cannot be justified by these benefits.

The final and most consequential attribute of effect is its measurement. Inasmuch as this study is concerned with physical, rather than economic damage functions, all damages are expressed in physical or biological, rather than monetary terms. Typical general measures of damage are the severity of effect summed over the population at risk, or the number or fraction of individual members affected. Specific measures vary widely from one target area to another and are thus best tackled under the several target areas below.

2. Health Effects

The target category of health effects refers primarily to the effects of air pollutants on human health, since most animals are not permitted to live long enough to suffer appreciable damages from prevailing pollutant concentrations. The major considerations here are the types of effects experienced, the effects of specific pollutants and cofactors, and the specific measures of damage.

The types of effects of air pollutants on human health, in order of increasing severity, are:

- Body burden
- Uncertain physiological changes
- Adverse physiological changes
- Morbidity
- Mortality.

At any given level of exposure, the fraction of the population affected decreases with increasing severity of effect, but damages in all of these categories must be included in the total figure.

Body burden, i.e., the accumulation of air pollutants (e.g., heavy metals), or their products (e.g., carboxyhemoglobin) in body organs and tissues, is the earliest indication of potential effect. This type of effect can be measured most reliably. Uncertain physiologic changes may involve decreased tolerance for exercise and changes in heart beat and blood pressure. Examples of adverse physiologic changes are eye irritation, coughing, and increase in electrocardiographic abnormalities.

Morbidity and mortality are by far the most common types of health effects investigated in the pursuit of damage functions. Large amounts of historical data are available from the National Center for Health Statistics, the National Heart and Lung Institute, the National Cancer Institute, and state departments of health. In most cases, the data are broken down by specific disorder, and sometimes, by demographic and/or socio-economic characteristics of the population at risk.

Measures of morbidity include incidence (number of new cases per unit time) and prevalence (number of continuing cases per unit time) of disease, hospital admissions and occupancy, medical visits, absenteeism from school and work, and personal record of discomfort. Some of these can be measured with greater reliability than others but most rely on weak reporting procedures. Mortality data suffer from occasional errors in diagnosing the cause of death, especially in the absence of an autopsy. Thus, specific heart ailments may be improperly identified and metastasized cancers mistaken for primary ones. Most importantly, there is no attempt to recognize combined effects, such as aggravation of the cause of death by another pollution-induced disorder.

The specific health effects of major air pollutants are listed in Table 20. It will be noted that aggravation of respiratory and cardiovascular diseases are the most common effects.

Table 20. Health Effects of Major Air Pollutants

Effect	Pollutants			
	SO _x / Particulates	NO _x	Oxidants	CO
Aggravation of respiratory disease	X	X	X	
Aggravation of cardiovascular disease	X	X	X	X
Suspected contribution to respiratory neoplasms	X	X	X	
Suspected contribution to gastrointestinal neoplasms	X			
Reduced lung function	X		X	
Eye irritation	X		X	
Chronic nephritis		X		
Impaired exercise tolerance and mental activity				X

The principal cofactors of air pollutants in human health effects are the meteorological conditions of temperature and humidity. Factors affecting susceptibility of the population at risk, such as smoking habits, occupational exposure, and general health, are accounted for in characterizing the population at risk.

3. Vegetation Effects

Effects of air pollutants on vegetation are manifested through physiological changes, various types of injury to leaves and other parts of the plant, reduced yield, reduced plant growth, and, of course, death. The relative consequences of the various types of effect depend on the plant species and use. Thus, leaf appearance is of paramount importance in the case of cigar tobacco, lettuce, and ornamentals, fruit yield is important in the case of fruit trees, whereas plant growth is a principal consideration in raising livestock fodder.

The most remarkable feature of past measurements of air pollutant effects on vegetation is their wide diversity. This frustrates any attempts at verifying, comparing, or aggregating the results of different studies. The problem is illustrated in Table 21 which shows the effect, the measurement technique, and the plant investigated.

Table 21. Measurement of Vegetation Effects

Effect	Measurement Index	Plant
Physiologic Change	Evapotranspiration	Tobacco, soybean
	Absorption of CO ₂	Pine
	Chlorophyll content	Tomato, pinto bean
Injury	Portion of leaf area affected	Nearly all plants studied
	Time to appearance	Elm, maple, ginko
	Leaf drop	Orange, lemon, pine
Growth Reduction	Weight	Ryegrass, soybean, birch
	Height	Cotton, poinsettia
	Diameter	Poinsettia, pine, poplar
	Number of leaves	Ryegrass
Yield	Number of flowers	Cotton
	Number of fruits	Cotton, orange, lemon, tomato
	Fruit drop	Orange
	Weight	Soybeans, corn, potato, tomato, spinach, radish, lettuce, alfalfa, orange, lemon
	Time to appearance	Corn, carnation, geranium, poinsettia, orange
Death		Mosses, lichens

Leaf injury may take the form of chlorosis - loss of chlorophyll manifested by appearance of light-colored areas, senescence - aging of tissues with concomitant changes in pigmentation, and necrosis - death of tissues evidenced by appearance of brown or black spots. Severity

of injury is expressed as the percentage of leaf area affected or the time to appearance of the injury. Extent of leaf injury has been used with some success to predict yield loss from sulfur dioxide and fluorides, but not from ozone. This may be associated with the fact that the former pollutants accumulate in the plant tissues to produce leaf injury, whereas ozone affects permeability of the cell membrane and interferes with normal function of the chlorophyll.

Major cofactors in effects of air pollutants on vegetation are meteorological conditions, such as humidity, precipitation, insolation, temperature, and air turbulence, as well as soil moisture and nutrient content. Mixtures of sulfur dioxide and nitrogen dioxide may produce synergistic effects. However, sulfur dioxide and ozone may produce effects that are synergistic, antagonistic, or merely additive, depending on concentration ratio and plant species. Insects, diseases, drought and inadequate nutrition can produce effects that mimic those of air pollutants.

4. Material Effects

Effects of air pollutants on materials are rather well defined in comparison with health or vegetation effects. This is due to the higher uniformity of samples, simpler damage mechanisms, and consequently, greater reproducibility of results. The principal effects may be classified as soiling, fading, coating, corrosion, and degradation.

Soiling of building and other exposed surfaces occurs through deposition of particulate matter. The resultant damage is measured in terms of change in surface reflectance, or more subjectively, in terms of the frequency and effort of cleaning. Fading of textile dyes and paints, attributed primarily to nitrogen oxides and oxidants, may be assessed by subjective inspection or optical measurements. Changes in the tensile strength of textiles, rubber, and leather products provide a measure of the degradation of these materials by sulfur dioxide and/or oxidants.

Corrosion and degradation of metal and masonry surfaces can take place through disruption of a protective coating (e.g., the oxide coating on aluminum), formation of an undesirable coating (e.g., the sulfide coating on copper or silver), and formation of a soluble compound or powder that is washed or blown away (e.g., zinc or calcium sulfate). Corrosion and degradation mar the appearance and reduce the strength of the materials which then require periodic surface refinishing or replacement. These effects can be measured in terms of changes in weight, thickness, or electric resistance of a metal contact.

The more important factors affecting the attack rate of materials by damaging pollutants include humidity, temperature, sunlight, and air turbulence. Humidity is particularly effective in the corrosion of metals and the critical value which produces a sharp rise in corrosion rate varies between 60-90 percent, depending on the specific pollutant and target metal. Wind speed is significant in enhancing the contact of pollutants, including abrasive particles, with the material surface. Elevated temperature generally increases the rate of chemical attack. Sunlight contributes to the formation of photochemical oxidants, but also mimics the rubber cracking and dye fading effects of ozone.

Presence of particulates appears to increase the corrosion rate of metals by sulfur dioxide. However, photochemical oxidants tend to reduce this rate, perhaps by forming a protective metal oxide coating.

E. ESTIMATION OF FUNCTIONAL RELATIONSHIP

Once the exposure and effects data have been collected through one of the types of studies discussed in the preceding section, it becomes necessary to apply various statistical methods to estimate the corresponding dose-effect relationships. These techniques, the inherent assumptions and errors, and the types of ensuing relationships are taken up here.

1. Statistical Methods

In classical hypothesis testing, it is usually assumed that the functional specification of the relationship being examined is given and that the relevant variables are known. Procedures can then be adopted from statistical theory to test competing hypotheses. In examining air pollution dose-effect associations, however, the functional form of the relation is seldom known, and there are only conjectures as to all the relevant factors. Nevertheless, it is often necessary for investigators to assume a functional form of a dose-effect relation and test it to see how well the data fit the assumption or whether modifications must be made, or alternative methods used.

The more common statistical methods for defining the quantitative relationship between exposure and effect are:

- Cross tabulations or simple correlations
- Multivariate regression analysis
- Distribution-free analysis.

The first method has been used in the health effects area to correlate the prevalence of a disease in specified population groups with an index of air pollution. The difficulty in using the results of such a study is that a host of other factors are allowed to vary across populations and it is usually impossible to identify the pure pollution effect.

Recognizing the need to control for confounding factors affecting dose-effect relationships, some investigations cross-tabulate along

several dimensions. For example, a statistical analysis of pollution effects on house paint might collect data for different areas of the country on the frequency of repainting, the levels of air pollution, and several meteorological variables. One could then compile either cross-tabulations based on the different variables or partial correlations. However, even this method will not produce reliable estimates of the dose-effect relation if the areas being compared are not well matched with respect to other important factors (e.g., types of buildings, or painting techniques).

A classic statistical method in epidemiological studies involves "purification" of the data by holding constant a number of factors. To this end, investigations of health effects have focused on persons of the same occupation and living in the same community, on the assumption that uncontrolled factors would be constant or vary randomly. However, a number of such studies suffer from large sampling variations induced by small sample sizes.

2. Multivariate Regression Analysis

Multivariate regression analysis of large populations has been used effectively to define the dose-effect relationship in health effects studies through statistical control of the interfering factors. The two basic types of multivariate analyses in this application use cross-sectional and time-series data, respectively. The first of these investigates a measured effect (e.g., mortality rates) across regions with different air pollution levels, while controlling for other regional differences, such as socioeconomic characteristics (Lave and Seskin, 1973). The second type of investigation examines changes in a measured effect within a single location as a function of changing air quality over a period of time (Glasser and Greenburg, 1971).

The major advantages of the time-series approach are that many of the covariates that could distort the results remain relatively constant within a region and that it permits assessment of lag effects. On the other hand, time-series analysis correlates current effects with current or lagged measures of exposure, even though these effects reflect preponderantly prior exposure, probably at lower concentration

levels. Thus, this approach is better suited to investigation of acute than of chronic effects. Moreover, this approach is subject to difficulties introduced by the assumption of serial independence of successive deviations between estimated and observed values.

The operation of multivariate regression analysis can be best illustrated by a simple two-variable case. The standard procedure for analyzing the relationship between the two variables is to fit a line through the observations using an ordinary "least squares technique", which minimizes the sum of squared vertical distances between the actual observations and the fitted line. The output consists of the best, linear, unbiased estimates of the slope and intercept. In the case of several independent variables, the results include coefficients which indicate the correlation between each independent variable and the dependent variable.

If the relationship is not approximated well by a linear equation, several other approaches can be used. A common procedure is to perform piecewise linear regressions by approximating several segments of the curve by linear functions. Another is to employ the cumbersome polynomial multivariate regression analysis. A third method is probit analysis, which usually involves representation of the independent variable on a logarithmic scale and expression of the dependent variable in terms of the probability unit (Finney, 1971).

Multivariate regression analysis has a number of important advantages:

- It provides a rapid estimate of the degree of association between a number of independent variables and the dependent variable
- If the independent variables are standardized, the individual regression coefficients can reveal the contribution of both "strength" and "sense" of each independent variable to the dependent variable
- It accounts for "unexplained" variations in the independent variable
- The required computer programs and know-how are widely available.

The limitations of this method are substantial, but can be mitigated somewhat by adroit statistical techniques.

- It requires a priori specification of an approximating relationship between each independent variable and the dependent variable
- Users frequently assume a linear relationship, and hence, the additive character of contributions of the independent variables
- Users frequently employ incorrectly an unweighted version that requires independent and randomly distributed errors in the dependent variable, with negligible randomness in the independent variables
- Regression coefficients are very sensitive to outlying data points.
- Regression coefficients are quite imprecise if the independent variables are closely correlated.

3. Distribution-Free Analysis

If the assumptions about distribution and relationships of the variables cannot be justified, the analyst has recourse to what is referred to as a distribution-free or non-parametric method of analysis. This method places little emphasis on population parameters, because the objective is to avoid a particular form for a population distribution. The hypotheses to be tested usually relate to the nature of the distribution as a whole, rather than to the values assumed by some of its parameters. This method of analysis can be implemented by comparing medians, means, ranges, ranks, or other classifications of data.

A distribution-free analysis based on medians was used to good advantage in investigating the health effects of sulfur oxides and nitrogen dioxide (Sprey and Takacs, 1973). The procedure may be outlined as follows:

- The range of each of the n independent variables is divided into classes (or levels)

- For each n-way classification of the data, the medians (or specified percentile) of the dependent and independent variables are computed
- The median of the first independent variable is plotted against the median of the dependent variable by classes of the first independent variable at various levels of the successive independent variables.

The set of medians are then estimates of the response of the dependent variable to all combinations of levels of the independent variables. Individual pairs of medians can be tested for statistically significant differences using standard median tests.

Another illustration, based on comparison of ranks, may involve the comparison of some measure of an air pollutant between Regions A and B, where n randomly selected samples of the air pollutant measured are available from each region. One can rank these 2n samples on the basis of their numerical values. The sum of the n ranks for Region A is then a measure of its overall pollution level. The minimum value that this sum can take occurs when each of the n values in Region A is smaller than the smallest value measured for Region B. Conversely, the maximum value that this sum can take occurs when each of the n values in Region A is larger than the largest value measured for Region B. If Regions A and B have the same overall pollution levels, we would expect this sum to lie approximately half-way between its minimum and maximum values. The distribution of this sum is readily calculable without any assumptions regarding the actual distribution of the pollutant levels within either of the regions, thus providing a distribution-free method for comparing the pollutant levels of the two regions.

The principal advantages of the distribution-free method of analysis are:

- Freedom from assumptions about distribution and relative dimension of errors
- Freedom from assumptions about a priori knowledge and/or linearity of the relationships between independent variables and the dependent variable

- Specificity of association between an independent and the dependent variable through use of two-way analyses of two independent variables.

On the other hand, this method is quite laborious, calls for interposition of human judgment at every step of the analysis, and requires large amounts of valid data to test the statistical interaction of several variables. Because of these onerous requirements, the distribution-free method of analysis is used only when multivariate regression analysis is not applicable.

4. Impact of Cofactors and Covariates

A recurring theme throughout this chapter has been the impact of cofactors and covariates on definition of the dose-effect relationship. Cofactors are usually defined as factors that mimic or act in concert with air pollutants, whereas covariates may be thought of as factors that vary jointly with the principal variable. The distinction is obviously very fuzzy and the two terms do get used interchangeably.

The principal covariates in air pollution effect studies may be listed as follows:

- Other pollutants
- Meteorological conditions
 - Humidity
 - Temperature
 - Precipitation
 - Wind speed and turbulence
 - Mixing height
 - Sunlight
- Other exposure
 - Occupational
 - Residential (including smoking)
 - Influenza
- Personal characteristics
 - Age
 - Race
 - Sex
 - Genetic factors
 - General health

- Socioeconomic characteristics

- Medical care
- Nutrition
- Exercise habits
- Occupation
- Income
- Education
- Housing
- Population density

- Timing

- Days of week, or month
- Holidays
- Seasons

An ideal investigation of the specific effects of an air pollutant would hold constant, or control all likely covariates. This can be accomplished, respectively, by judicious design of the investigation, or by statistical techniques. Personal and socioeconomic covariates may be held constant by employment of time-series investigations or selection of comparable populations in cross-sectional studies. All studies should discount seasonal and other temporal variations.

A good illustration of the statistical techniques is provided by a classic multivariate regression analysis of the association between mortality and air pollution, which controlled many of the covariates listed above (Lave and Seskin, 1973). One of the most serious problems was found to be multicollinearity, which occurs when some of the independent variables are so highly correlated with one another that it becomes nearly impossible to isolate and estimate their individual impacts. Techniques available to treat these difficulties include the use of principal components (Harman, 1967) and ridge regression (McDonald and Schwing, 1973), but their application is frequently accompanied by other undesirable features.

Unfortunately, in most cases, there are factors which elude control. Some of these are difficult to measure conceptually, while others suffer from poor availability of data. Other problems arise when there is a factor that is the actual cause of both a given air pollutant and its effect. This could be illustrated by the role of sulfur dioxide in the formation of ozone and damage to plants. Such a factor would give rise to a spurious correlation between the air pollutant and the effect being investigated (Simon, 1954).

F. PRESENTATION OF RESULTS

The utility of a dose-effect function is heavily dependent on the format and meaningfulness of its presentation. This last section takes up the types and quality of relationships encountered, selection of measures, and nature of errors and uncertainties.

1. Types of Dose-Effect Relationship

The classical representation of the relationship between exposure and effect takes the form of a sigmoid, or S-shaped curve shown in Figure 30. The ordinate may represent either the number of individuals affected or severity of effect. The abscissa indicates the dosage in terms of time at a given ambient concentration, or in terms of ambient concentration for a fixed period of time. The lower portion of the curve suggests that, up to a low exposure value, known as the threshold level, no effect has been observed. The upper portion indicates that there exists a saturation level (e.g., death of the target population or total destruction of the crops), beyond which increased exposure does not produce additional effect. The middle, quasi-linear portion is very useful in that any data points here can be readily interpolated, and the frequent assumption about linearity of a dose-effect function is most valid in this sector.

Nearly all the graphs of dose-effect functions reviewed in the course of this study represent some variation on this basic relationship. Most frequently, they involve the linear (Figures 3, 6, 7, 8, 9, 19, 22, 23) or curvilinear (Figures 14, 17, 20, 21, 24, 25, 28, 29) portions of the curve or some linear approximation (Figures 4, 11). A special case of the latter is known as a "hockey stick" function (Figure 31). Bar charts (Figures 5, 26) are more appropriate when exposure is expressed in terms of average values during changing intervals. Finally, effect can be expressed as a function of both concentration and exposure time, as well as several pollutants, or some cofactor of air pollution, with the aid of families of curves (Figures 8, 17, 20, 21, 24) or multi-dimensional plots (Figures 12, 13, 18).

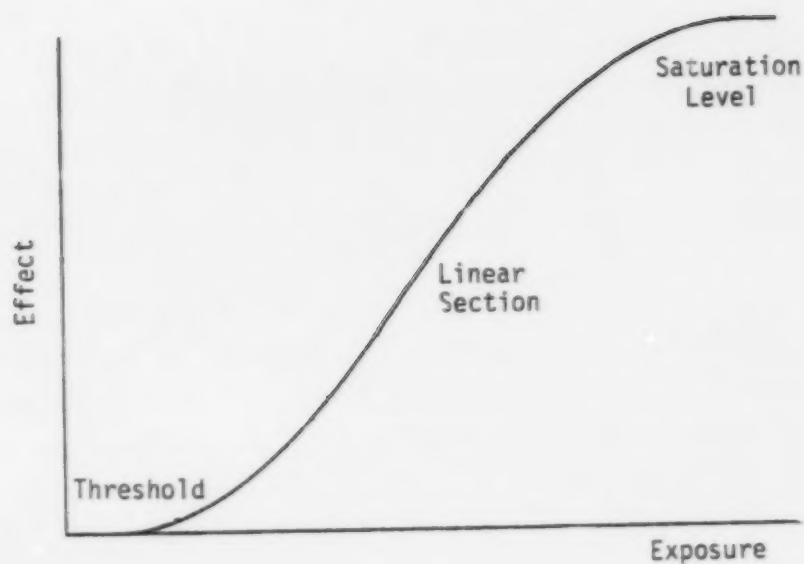
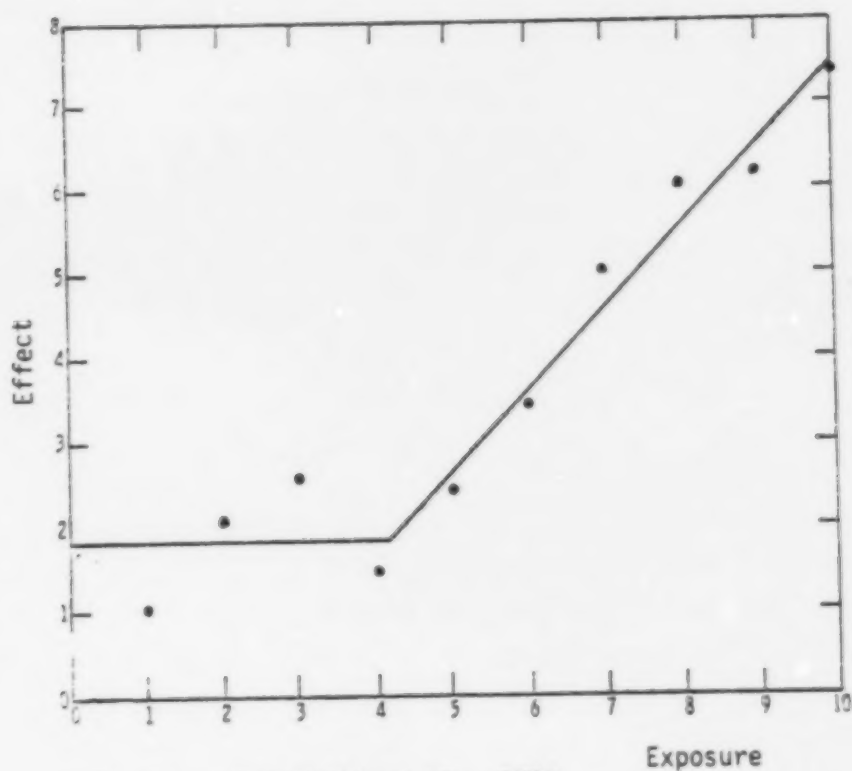


Figure 30. Hypothetical Dose-Effect Function



Source: Hasselbald et al., 1974

Figure 31. "Hockey Stick" Curve Fitted to Artificial Data

Some representative mathematical formulations are presented in Table 22. It may be noticed that there is no consistent pattern for expressing these relationships.

Table 22. Selected Dose-Effect Relationships

Relationship	Definition of Terms	Reference
<u>Health Effects</u>		
$MR_i = a_0 + a_1P_i + a_2S_i + e_i$	MR_i = mortality rate for a particular disease in area i ; P_i = measure of air pollution; S_i = measure of socioeconomic status; e_i = error term with zero mean	Lave and Seskin, 1972
$EMR = 0.00339 C - 0.660$	EMR = percent excess mortality; C = concentration of sulfur dioxide, $\mu\text{g}/\text{m}^3$	Buechley et al., 1973
<u>Vegetation Effects</u>		
$C = a + b_1I + b_2/T$	C = concentration; I = percentage of plant response; T = time; a = response threshold; b_1 = genetic resistance factor; b_2 = external resistance factor	Heck and Tingey, 1971
<u>Material Effects</u>		
$CR = 0.001028 (RH - 48.8)C$	CR = corrosion rate of zinc, $\mu\text{m}/\text{yr}$; RH = relative humidity; C = concentration of sulfur dioxide, $\mu\text{g}/\text{m}^3$	Raynie and Upham, 1970

2. Quality of the Relationship

The most general type of relationship between exposure and effect is termed "associative". This merely means that certain effects have been found associated with given levels of exposure of a population to a specific pollutant. Establishment of the more rigorous "causal" relationship requires the additional adducement of direct or indirect evidence of causation. In the case of human health effects, such direct evidence is difficult to obtain, and indirect evidence must be used. This is based primarily on a plausible mechanism and toxicological experiments using animals as surrogate subjects for humans. For vegetation and materials, controlled experiments can be conducted, showing that the effect occurs upon exposure to the given pollutant and does not occur when that pollutant is missing.

The evidentiary characteristics of a causal relationship include strength, specificity, and consistency. Strength of the relationship

may be measured by the degree of correlation between exposure and effect. Specificity refers to whether only the given factor can produce the observed effects. Consistency is tested by any departure from the established functional relationship. The increasing degrees of certainty of a causal relationship may be expressed by such terms as "suggested", "possible", "likely", and "definite".

3. Selection of Measures

Measures of exposure and effects are characterized by a unit of measurement (e.g., $\mu\text{g}/\text{m}^3$, excess deaths per 10,000), a specific pollutant, a given effect, an instant or interval of time, a geographic location, and a population at risk (e.g., white males over 65, Bel W₃ tobacco). These concepts were discussed in some detail in the preceding sections. Results of dose-effect studies are usually reported in terms of some combinations of the various levels of aggregation of these parameters (e.g., annual means, SO₂, and smoke shade 140 SMSAs, respiratory diseases, white males). Selection of units of measure and combination of levels of aggregation should be governed by the need to accommodate the likely user, the intended use, and the available data.

Likely users of the information are public officials, businessmen, taxpayers, and exposed citizens. Obviously, any one individual is apt to find himself in more than one role. Public officials and exposed citizens are more likely to be interested in dose-effect functions and health effects, whereas businessmen and taxpayers would have more use for economic damage functions which attach a monetary value to the physical and biologic effects in all target areas.

Intended uses may take the form of national pollution control policy, establishment of air quality standards, planning of regional development, reaching of business decisions, and selection of place of employment and residence. It may be noted that the required level of geographic and population aggregation decreases as one moves down the list to the point where an individual making a personal decision may be interested only in the effects of a given exposure on himself and his immediate family.

Finally, certain desirable units of measure or levels of aggregation may not be obtainable because of lack of adequate resolution in the original data. For example, the daily excess mortality rates from chronic bronchitis, associated with daily means of SO_2 concentrations for white males over 65 obviously cannot be recovered from exposure data reported in monthly averages or from mortality rates that are not age or cause-specific.

4. Nature of Errors and Uncertainties

Errors in representing dose-effect functions may be characterized as errors of specification and measurement. The former include any type of error in specifying the functional form of the relationship under study or in accounting for important variables. A particularly common and grave error of specification is committed in attempting to extrapolate a complete functional relationship from a few data points that are barely adequate to characterize a small portion of the curve. Even if one were willing to make an assumption about the overall shape of the function, there is frequently no way of knowing which portion is represented by these data points.

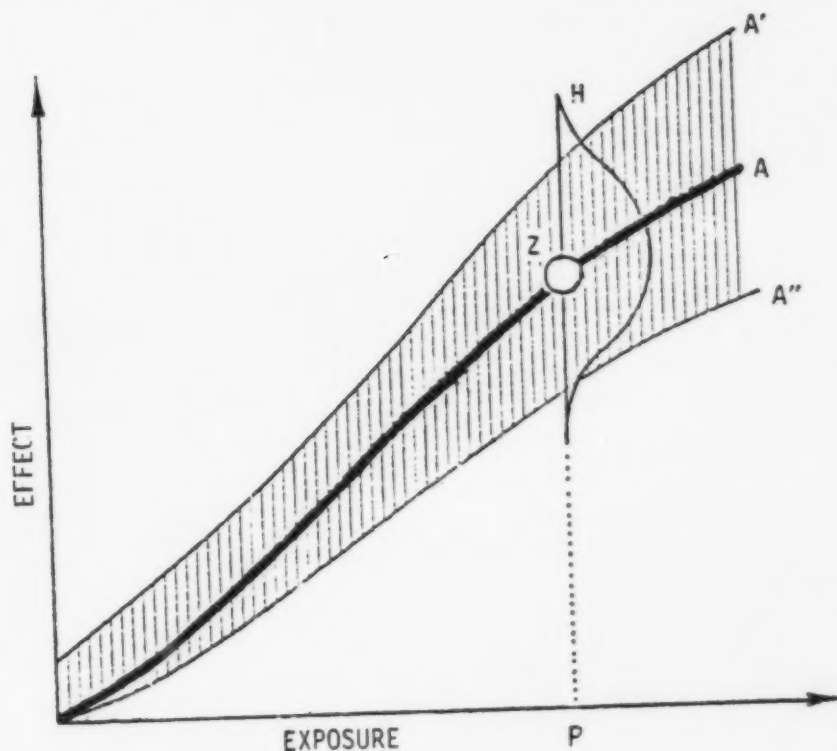
Errors of measurement have been alluded to throughout the several sections of this chapter and may be incurred in the course of the following steps and aspects of the development process:

- Ambient levels
 - Station location
 - Sampling
 - Analytical measurement
 - Averaging and aggregation of ambient levels
- Exposure
 - Location of subjects
 - Determination of exposure
- Effects
 - Determination of effect
 - Impact of cofactors, covariates, and mimics
 - Characterization of population at risk

If the errors of measurement of the independent variables are relatively small, occur at random, and follow a normal, or Gaussian distribution about the mean value of each variable, then the total error of all the independent variables can be computed by standard statistical techniques. This can then be compared to the error of measurement of the dependent variable (effect) to determine the overall uncertainty of the functional relationship between dose and effect, and of the estimated impact of the various covariates. However, this is seldom the case, because measurement of such independent variables as pollutant level, meteorological conditions, and socioeconomic characteristics is subject to errors that are both large and biased.

5. Display of Uncertainties

The representation of errors of measurement and the ensuing uncertainties in the results is illustrated in Figure 32. Here, a point Z lying on the dose-effect curve A represents only the average or expected number of effects or affected subjects associated with



Source: Abel, 1974

Figure 32. Display of Uncertainty in Dose-Effect Function

exposure P. The actual measurements are characterized by some frequency distribution about point Z which, in the idealized Gaussian case, can be represented by curve H. If the variance of the points along curve A is known, then confidence limits can be calculated and represented by confidence bands A' and A".

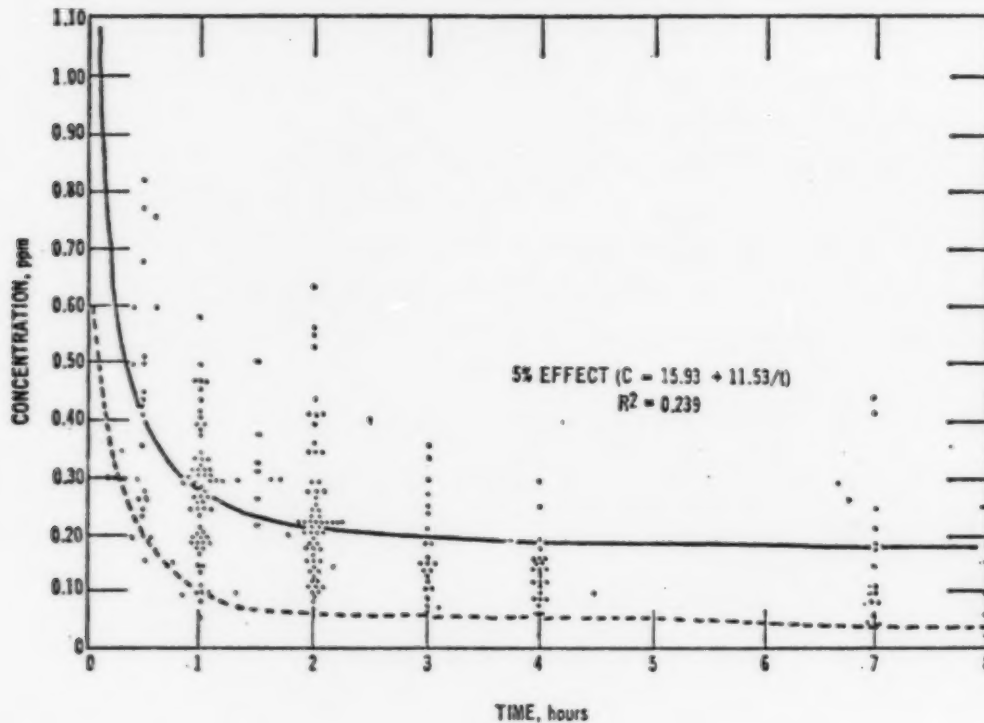
In actual practice, envelopes characterizing errors and uncertainties of dose-effect functions have been obtained by other means, including:

- Replicating a specific study with use of new data
- Manipulating values of the more important variables
- Combining results of several studies
- Applying "best" and "worst" case assumptions
- Bounding available data points.

Replication and data manipulation are essentially empirical techniques of determining the errors and corresponding confidence bands. Combining the results of several studies is a rare and uncertain opportunity, in light of the great variety of conditions and populations that characterize the different efforts (see Figure 33).

Application of "best" and "worst" case assumptions is more an argumentative than a statistical technique. The lower boundary, or best case, is established by attributing all reasonable portions of the effect to any plausible cofactors and covariates and associating only the residual effects with pollutant exposure. The upper boundary, or worst case, is determined by inverting this procedure and assuming a minimal impact of other variables. (Finklea, 1973).

Bounding of data points by one or two boundary curves is indicated in cases where the data points are too scattered to justify plotting a simple curve. Such boundaries fall short of constituting a dose-effect function, but do provide some idea of the range of effect.



Source: NATO, 1974

Figure 33. Ozone Concentration Time Scatter Diagram of 5% Acute Plant Responses From Over 100 Species and Varieties Calculated From Data Taken From References; Dotted Line Approximates an Acute Response Threshold.

6. Merits and Failings

Properly constituted and qualified dose-effect functions can serve as valuable instruments in meeting the following intermediate objectives in the public decision-making process:

- Popular conceptualization of the threats posed by various levels of environmental pollution and the beneficial changes expected from pollution abatement.

- Planning of residential, commercial, and industrial development, including siting, transportation, and utilities
- Planning national and regional pollution control policy
- Establishment of environmental quality standards designed to protect public health and property.

Unfortunately, development of dose-effect functions has suffered from a number of failings which have necessarily limited their potential role. Among the most salient of these are:

- Insufficient data, requiring daring extrapolations of a curvilinear function from only a few data points
- Lack of proper representation of the uncertainty of the functional relationship
- Failure to account properly for the impact of other pertinent variables and for synergistic interactions among pollutants
- Attempt to represent complex and dynamic relationships by quasi-linear and static functions.

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IV. ANALYSIS OF SELECTED FUNCTIONS

This chapter provides an in-depth analysis of selected dose-effect functions to determine how they could be rendered more valid and useful to potential users. The first section is devoted to selection of three functions, whereas the remainder of the chapter contains the analyses of each function, based on the methodology discussed in the preceding chapter.

A. SELECTION OF FUNCTIONS

Dose-effect functions for in-depth analysis are selected here for each of the three major damage categories (health, vegetation, and materials) and two of the five major pollutants (particulates, sulfur dioxide, nitrogen dioxide, oxidants, and carbon monoxide), for which significant studies have been carried out on the basis of their relative importance and validity.

1. Selection Criteria

The impact of a dose-effect function on potential policy decisions may be determined by four criteria:

- Importance of effect
- Data quantity and compatibility
- Data quality
- Validity of function.

Importance of effect may be assessed in terms of the resulting loss to society. Quantity and compatibility of data are interrelated, because only data from compatible studies can be legitimately combined to expand the data base. The notion of compatibility encompasses exposure and effect indices, dose rate, target population, geographic area, and time frame. Data quality can be judged on the merits of their source, precision, and accuracy. Finally, function validity can be determined on the basis of how well the curve fits the data, the

statistical methods used, and the validity of assumptions used in estimation of the functional relationship, as well as the consistency and plausibility of the observed association.

The relative weighting of each criterion in the selection process depends on the category of effects, specific objectives of the selection process, and the subjective considerations of the analyst. For example, in the area of human health, a function reporting the impact on mortality may be considered of overriding importance. In the area of vegetation damage, crop yield may be of more direct economic significance than leaf injury, though poor compatibility of the yield data might force the use of a narrow data base. In the materials area, there is little conflict between the economic importance of the effect and the size of the data base. This is probably due to the fact that material effects are more easily quantifiable from a physical and chemical standpoint.

Analytical considerations to be addressed during in-depth analysis of damage functions include:

- Measurement of ambient levels
- Determination of dose and dose rate
- Selection and aggregation of dose indices
- Determination of effects
- Selection and aggregation of effect indices
- Characterization of population-at-risk
- Validity of dose-effect relationship
- Characterization of errors and uncertainties
- Relation to criteria and standards
- Relation to other studies.

The damage functions selected are analyzed with respect to these considerations and resultant conclusions and the recommendations are formulated in the major sections that follow. The analysis is based on the methodology covered in the preceding chapter.

2. Selection Process

Major Air pollutants and their effects were listed in Table 1. The corresponding dose-effect functions that appear as likely candidates for in-depth analysis are presented in Table 23.

Table 23. Candidate Dose-Effect Categories for In-Depth Analysis

Area	Pollutant	Effect
Human Health	Sulfur oxides	Mortality
	Sulfur oxides	Respiratory illness
	Oxidants	Impairment of respiratory function
	Oxidants	Eye irritation
	Nitrogen oxides	Mortality
	Nitrogen oxides	Respiratory illness
	Carbon monoxide	Aggravation of heart disease
	Carbon monoxide	Behavior impairment
Vegetation	Sulfur oxides	General damage
	Oxidants	General damage
	Oxidants	Leaf injury
	Oxidants	Yield reduction
Materials	Particulates	Paint deterioration
	Sulfur oxides	Metals corrosion

All of the health effects listed rate highly under the importance criterion, with the possible exceptions of eye irritation and behavior impairment. Data quantity and quality for the first two health categories are satisfactory, although studies in the second category have been done for different geographic areas and population groups and may not be fully compatible. The effects of nitrogen oxides have not received adequate study. A good epidemiological and toxicological data base exists for the effects of oxidants and carbon monoxide.

The importance of effects of air pollutants on vegetation lies in the extent of damage which they may cause to the nation's agricultural crops valued at nearly \$40 billion annually, as well as to the forests and ornamental plants. Oxidants are potentially the most damaging pollutants and the data base for oxidants is very extensive. However, the results of the many different studies are not compatible, because they were performed for different plant species and under varying conditions and exposures. For this reason, consideration of a specific genus, or at least type of plant, such as pine, citrus, or tobacco, would be more appropriate. A substantial data base has been generated for sulfur oxides as well. However, the effects of fluorides have been investigated less extensively, primarily because of their localized occurrence.

The pollutants implicated in damage to materials are primarily particulates and sulfur oxides. The data base is severely limited by the small number of studies, but the results of these are highly quantitative and cover a greater range of values than do studies in vegetation or health effects. The reason for this is the greater opportunity to conduct controlled laboratory tests of these effects. The effects of acute and chronic exposure of steel, zinc, copper, and aluminum to sulfur oxides have been investigated extensively, under both ambient and laboratory conditions. In the case of steel and zinc, studies have been conducted in both urban and rural locations. The only potential compatibility problems are those associated with use of currently disqualified air pollutant monitoring techniques and exposure of different alloys of these metals.

In light of all these considerations, the following three dose-effect functions were selected for in-depth analysis:

- Sulfur dioxide (or sulfates) - human mortality
- Ozone - injury to tobacco leaves
- Sulfur dioxide (or sulfates) - corrosion of zinc.

B. EFFECTS OF SULFUR DIOXIDE ON HUMAN MORTALITY

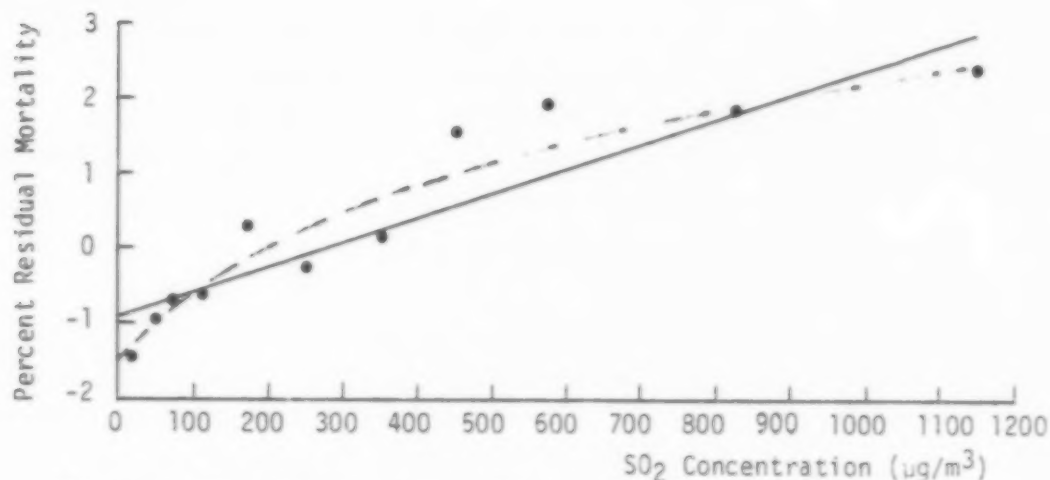
Effects of sulfur dioxide on human mortality represent the most intensively studied area of air pollution effects. The specific study analyzed here is among the best in this area. The analysis here follows the general outline formulated in Section A.

1. Description

The dose-effect function selected to represent this pollutant-effect category was originally presented in 1972 at a Medical Research Conference and published a year later by Buechley *et al.*, (1972, 1973). It established daily SO₂ concentration as a significant predictor of daily mortality in a large, densely populated, highly polluted metropolitan area. The function is shown in Figure 34 and may be expressed by the equation:

$$\text{Percent Residual Mortality} = 0.00339 (\text{SO}_2, \mu\text{g}/\text{m}^3) - 0.860$$

The underlying data are displayed in Table 24.



Source: Based on Buechley, 1975

Figure 34. Relationship Between Daily Residual Mortality and Sulfur Dioxide Concentrations for the New York-New Jersey Metropolitan Area During 1962-1966; Solid and Dashed Plots Represent Two Possible Fits.

Table 24. Daily Sulfur Dioxide Concentrations and Daily Residual Mortalities for the New York - New Jersey Metropolitan Area During 1962-1966

SO ₂ Concentration, in µg/m ³	Duration, in Days	Daily Mortality, As Percent Deviation From Mean
15 (0 - 30)	232	- 1.47
45 (30 - 60)	120	- 0.98
70 (60 - 80)	130	- 0.68
110 (80 - 140)	210	- 0.62
170 (140 - 200)	212	0.27
250 (200 - 300)	275	- 0.26
350 (300 - 400)	184	0.16
450 (400 - 500)	203	1.54
575 (500 - 650)	99	1.94
825 (650 - 1000)	114	1.85
1150 (1000 - 1300)	47	2.40

Source: Buechley, 1975

2. Determination of Exposure

The area covered by this study was approximately the New York-New Jersey-Connecticut air quality control region, with a 1960 population of 13,760,112. The measurements of air quality for the entire area were based on readings from only one air pollution monitoring station operated nearly continuously during the 1962-1966 period: the 121st Street Davis Laboratory in Manhattan. Gaps in the data were filled by reference to other stations, or by estimation. An analysis by Blade and Ferrand (1969) of 1957-1968 records for New York City shows that the Davis Laboratory observations were acceptably representative of readings for the area and especially of relative levels. This is not unexpected, because the entire area is replete with point and area sources of SO₂.

The specific measure of concentration was obtained by averaging hourly concentration readings over each 24-hour period. The resulting variable can be regarded as either an average concentration or a dosage, since all time periods were equal. Determination of dose (actual intake of pollutants), as distinct from dosage (opportunity to take in pollutants), is not important for the purpose of this study, because its task is to relate variations in ambient concentrations

to health effects. The averaging process may conceal short concentration peaks and yield erroneous results for acute effects.

3. Determination of Effect

The population at risk was the entire population of the area and the measure of effect was total mortality. Buechley et al. (1973) had analyzed mortality data for 422 localities in the United States, and the New York study represented a subset of this study for which acceptable air quality records were available. The total number of deaths for the five-year period, after eliminating the effects of "disasters" and "time trends", was 754,219. A mean daily death rate of 413.04 was obtained by dividing this total by the number of days (1826). Finally, the observed deaths on a given day were divided by 413.04 to give the mortality ratio for that day. Cause-specific deaths were not considered, with the exception of influenza-pneumonia.

The determination of effect was flawed in several respects. First, by looking at daily averages, the study emphasized acute at the expense of chronic effects. Obviously, the mean daily death rate and the mortality ratio for any given day were the result of many years of exposure and their correlation with daily exposure can only represent the terminal step in that process. Conversely, the effect of an exposure on any given day is likely to be reflected in a death occurring years later.

Moreover, the study failed to account for individual differences in susceptibility among the various classes of the population at risk. The effects of SO_2 exposure would be expected to impact most severely on certain classes of the population, such as infants, the aged, heavy smokers, and sufferers from advanced pulmonary or cardiovascular disease. The function for these classes would almost certainly indicate a higher level of damage and a different slope. Such a refinement would have further validated the results of the study by noting whether effects follow the expected trend, and would have afforded useful additional information to potential users. A similar argument could be made for the desirability of specifying the cause of death.

4. Estimation of Dose-Effect Relationship

Multiple regression analysis was used to estimate the individual contributions of a number of variables to the mortality ratio. The following covariates were identified:

- Major covariates
 - Annual cycle
 - Extreme heat
- Intermediate covariate
 - Influenza epidemics
- Minor covariates
 - Warm and cold weather
 - Holidays (Christmas and New Year only)
 - Day of week
 - Sulfur dioxide
 - Coefficient of haze.

Other cofactors were tested without success.

With the other covariates controlled, sulfur dioxide was a significant predictor. Table 23 shows that mortality was 1.5 percent less than expected on 232 days with SO_2 concentrations below $30 \mu\text{g}/\text{m}^3$, and 2 percent greater than expected on 260 days with SO_2 concentrations above $500 \mu\text{g}/\text{m}^3$. However, the coefficient of haze and smoke for 1965-1966 did as well as SO_2 in predicting deaths.

The use of SO_2 concentration as the index of air quality does not imply a direct causal relationship with mortality. Toxicological evidence points to the fact that SO_2 , acting alone at these levels, is no worse than a mild irritant. Other evidence indicates that sulfates, which may be formed from the SO_2 , are much more toxic, that there exists an association between sulfates and mortality, and particulates can have a synergistic effect. It is, therefore, quite likely that, in showing an association with mortality, SO_2 measurements are acting as a proxy for sulfates, for SO_2 and particulates, or perhaps for some other species.

These considerations restrict the applicability of the damage function in locations, where the distribution of pollutants may differ significantly from that prevailing in the area under study. If the synergistic effect of SO_2 with particulate pollution is important, the function may not apply in areas of different particulate pollution level. Similarly, the rate of formation of sulfates and their precise composition are affected by environmental factors which differ from place to place. Finally, SO_2 is an adequate proxy for other pollutants only insofar as their relative emission rates and distributions are similar.

5. Display of Results

The data points in Figure 34 can be fitted reasonably well by a straight line, considering the limitations of the data base. However, an even better fit is a portion of the classic S-shaped curve, and in fact, the authors plotted the results as a logarithm of the dose vs. a linear measure of effect.

The form of the relationship at the lower concentrations is of special interest. The linear plot exhibits no threshold, which implies that benefits from reduced pollution continue down to zero concentration. This suggests that inducement of death through acute aggravation of morbid conditions may not be the typical damage mechanism and that the association of daily pollution into same-day mortality may have more complex antecedents.

6. Relationship to Other Studies

Glasser and Greenburg (1971) attempted to explain deviations in New York City's daily mortality from a five-year "normal" on the basis of sulfur dioxide and smoke shade as measures of air pollution, as well as a number of climatological variables. With the aid of a regression analysis, they found a definite relationship between daily mortality and air pollution, as measured primarily by sulfur dioxide. The analysis also included rainfall, wind speed, sky cover, and temperature deviations as explanatory variables.

In a study of New York City data between 1963 and 1968, Schimmel and Greenburg (1972) obtained a similar estimate of the SO_2 effect using slightly different analytic techniques. They concluded that there were 10,000 deaths per year (12 percent of all deaths) in New York City "which would not have occurred at the time they did if there had been no pollution on the day of death or immediately preceding days".

Lave and Seskin (1973) studied the relationship between mortality rates and a large array of environmental, biological, and socio-economic factors in 117 standard metropolitan statistical areas. They found a substantial correlation between suspended particulates and sulfates and mortality and concluded that a 10 percent reduction in each pollution measure would reduce the mortality rate by 0.9 percent.

A comprehensive U.S. EPA report observed that aggravation of symptoms has been repeatedly demonstrated at daily SO_2 levels well below the indicated threshold for excess mortality. Health consequences ranging from functional changes preceding disease to death itself have been associated with SO_2 exposures in the range of $80\text{--}120\text{ }\mu\text{g}/\text{m}^3$ for one or more days. Daily sulfate levels in the $7\text{--}14\text{ }\mu\text{g}/\text{m}^3$ range have been associated with aggravation of symptoms in particularly vulnerable population groups.

Finally, it should be noted that both Buechley and Schimmel are in the process of revising their estimates of the quantitative impact of pollution on mortality, which they now believe to be substantially less, though still significant (Buechley, 1975). This in no way affects the value of the dose-effect function developed by Buechley et al. as an illustration of analytical methods and of some typical strengths and limitations of such work.

The air quality criteria published by NAPCA (1969) and updated by NATO (1971) are based on epidemiological studies which indicate that mortality increases may be observed above $500\text{ }\mu\text{g}/\text{m}^3$ (24-hour mean value) in the absence of heavy particulate pollution, and at values as low as $115\text{ }\mu\text{g}/\text{m}^3$ in smoky air. The corresponding standards are a 24-hour mean of $365\text{ }\mu\text{g}/\text{m}^3$ and an annual arithmetic mean of $80\text{ }\mu\text{g}/\text{m}^3$.

In the present dose-effect function, a 24-hour mean of $365 \mu\text{g}/\text{m}^3$ corresponds to an excess death rate of 0.4 percent with respect to the "normal" baseline.

An estimate of the annual mean corresponding to the 24-hour maximum value of $365 \mu\text{g}/\text{m}^3$, based on New York City data for 1973, is $93 \mu\text{g}/\text{m}^3$. This is in fair agreement with the annual mean standard of $80 \mu\text{g}/\text{m}^3$. The function indicates that, if this standard had prevailed in the years 1962-1966, the residual mortality baseline would have been about 0.6 percent lower.

7. Conclusions and Recommendations

The foregoing analysis suggests the following conclusions:

- The dose-effect function shows a valid relationship between daily residual mortality and daily SO_2 concentration for New York City during 1962-1966, despite the limitations of the data base and analysis
- The most serious defects of the study (which were generally recognized by the investigators) are the single monitoring station and the use of a pollutant which is probably not the causal factor
- The function may be an acceptable predictor for other places and times, but its applicability would require environmental and population factors similar to those encountered during this study
- The function does not support the existence of a threshold
- Further developments along similar lines, with a more detailed classification of the population at risk and specification of the cause of death, are highly desirable.

Consequently, the following actions are recommended:

- Monitoring of SO_2 , particulate, and sulfate levels at a sufficient number of stations to have a demonstrably representative measure of air quality

- Detailed analysis of the health effects as a function of exposure to sulfuric acid, acid and metal sulfates, and particle size
- Special attention to conditions at and below the national air quality standards
- Characterization of the population at risk, with emphasis on age, race, general health, smoking habits, and occupation
- Addition of other health-related damage functions, including aggravation of symptoms in chronically ill persons, impairment of lung function in healthy and ill persons, and contributions to the incidence of acute and chronic respiratory disease in various population subgroups
- Collection of cause-specific mortality data.

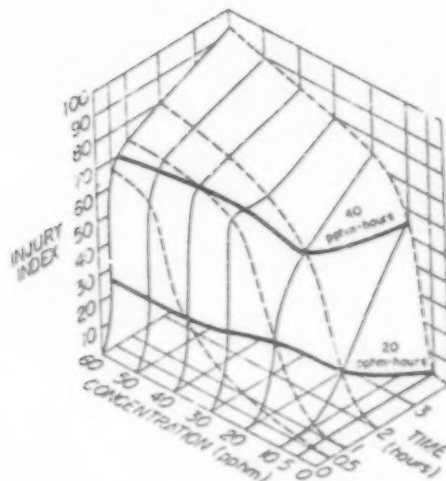
C. OXIDANT INJURY TO TOBACCO LEAVES

This section presents an in-depth analysis of the injury to tobacco leaves produced by elevated oxidant levels. The analysis follows the general outline formulated in Section A.

1. Description

Investigations designed to characterize injury to tobacco leaves by oxidants and related factors have been conducted by Heck et al. (1966), Menser and Heggstad (1966), Turner et al. (1972), Heagle and Heck (1974), and Taylor and Rich (1974). These studies were conducted under different exposures, experimental conditions, and measures of leaf injury, which makes it very difficult to reconcile the data or to integrate them into a self-consistent damage function.

The function selected for the present analysis was developed by Heck et al. (1966) for the Bel W-3 cultivar of tobacco (*Nicotiana tabacum* L.). The graph of the function, shown in Figure 35, provides a vivid demonstration of the different effects of the concentration and time elements of exposure on leaf injury, permitting the interpretation of both chronic and acute effects. Two equal-dose curves are indicated for 20 and 40 ppm-hrs.



Source: Heck et al., 1966

Figure 35. Relationship Between Oxidant Exposure and Injury to Bel W-3 Tobacco Leaf

2. Determination of Exposure

The plants were grown in controlled environment chambers approximating field conditions, including ozone levels, relative humidity, and temperature. Exposures were made at 0.1, 0.2, 0.3, and 0.55 ppm for periods of 1/2, 1, 2, and 4 hours. Each exposure was replicated four times, to produce the equivalent of four days' exposures, and administered to four plants, to achieve more representative results.

Ozone levels were measured with a coulometric MAST recorder which reads out the current necessary to maintain a constant halide concentration in a solution where the ozone has been absorbed. Within a certain range, the magnitude of the current is directly proportional to the amount of ozone absorbed. However, freshly generated ozone released and mixed with air may form other unmeasured and unreported oxidants, making the oxidant readings too low.

As was the case with health effects, it is not practical, nor even necessary to determine a dose that is distinct from the dosage, if experimental conditions remain basically the same or can be assumed to cancel out among populations. Differences between these quantities are due to evapotranspiration, which forms a protective barrier, air movement past the leaf surface, which has the opposite effect, and relative humidity, which regulates the opening of the plant's stomata and may affect the plant's susceptibility as well.

The concentration element of exposure is expressed in parts per hundred million (pphm), the time - in average number of hours in each of four days, and exposure - as product of concentration and time, or pphm-hours. It must be assumed that the dosage was kept constant for the duration of each exposure by some regulatory mechanism. However, in field situations, dosage exhibits both hourly and daily fluctuations and average concentrations may represent a poor approximation. Moreover, Heagle and Heck (1974) have shown that various exposures to oxidants produce varying predispositions of the plant to greater injury from subsequent exposures.

3. Determination of Effects

The leaf injury was manifested in the form of flecks, which make the leaf undesirable, or unacceptable, as cigar wrapper. In this case, therefore, there exists a direct correlation between injury and damage, or economic loss. The injury is measured in terms of an index, which is presumably based on the fraction of the leaf surface covered by the flecks, but otherwise is not clearly defined.

The fleck injury to tobacco leaves by oxidants may be caused by induced chemical interactions in the palisade and mesophyll cells leading to accumulation of toxic substances, degradation of cell membranes, and/or disruption of enzyme production. Extensive injury can decrease substantially the plant's photosynthetic capacity and reduce its growth.

The effect index selected by Heck et al. is based presumably on the fraction of leaf surface area covered by the flecks. Other indices listed below provide a less subjective, though not necessarily more appropriate, measure of damage:

- Reduction of leaf growth rate
- Reduction of photosynthesis
- Reduction of stomatal conductance.

The last two indices reflect a similar measure, since gas exchange limitations in the stomata affect the photosynthetic process. Moreover, changes in the efficiency of energy utilization by the plant's metabolic processes may compensate for the loss of photosynthetic capacity to some extent. Thus, reduction in leaf growth rate appears to provide the optimal measure.

Although tobacco represents economically the seventh most important crop plant, the Bel W-3 cultivar is not a commercial variety, but a research strain with a high susceptibility to ozone.

Cultivars 6590 and Connecticut 49 are considered moderately sensitive, and cultivar 6524 is ozone tolerant. The study gives no indication of the variation in effects between different plants of the Bel W-3 variety. This variation can be due to genetic variability, different growth stages, and varying environmental conditions, such as soil characteristics and leaf microclimate.

4. Validity of Dose-Effect Relationship

The graph in Figure 35 lends an informative representation of the effect of the concentration and time elements of oxidant exposure on tobacco leaf injury. It provides a vivid demonstration that dosage alone is not a sufficient measure of exposure.

The validity of the specific damage function presented as far as it goes, should be rather good, since it is based on results of controlled experiments. One major flaw, in light of recent indications of serious damage under these conditions, is the lack of long-term exposures to low concentrations under 10 ppm. A more definitive judgment would require information on variance of individual results for the different plants, as well as an analytical, or at least visual, measure of the fit of the curves with respect to the data points.

However, the extent to which this limited function represents the more general relationship between oxidant exposure and damage to tobacco is subject to all of the reservations expressed earlier, namely:

- Uncertain relationship between ozone measurements and oxidant concentration
- Failure to isolate the effects of meteorological factors
- Artificial flattening of concentration fluctuations
- Subjective measurement of damage
- Failure to characterize uncertainties.

The national primary and secondary air quality standard for photochemical oxidants is a one-hour maximum of 0.08 ppm not to be exceeded more than once per year. According to the meager data available, these standards are exceeded frequently in rural areas. The function suggests

that this may cause substantial damage to the more sensitive varieties of tobacco.

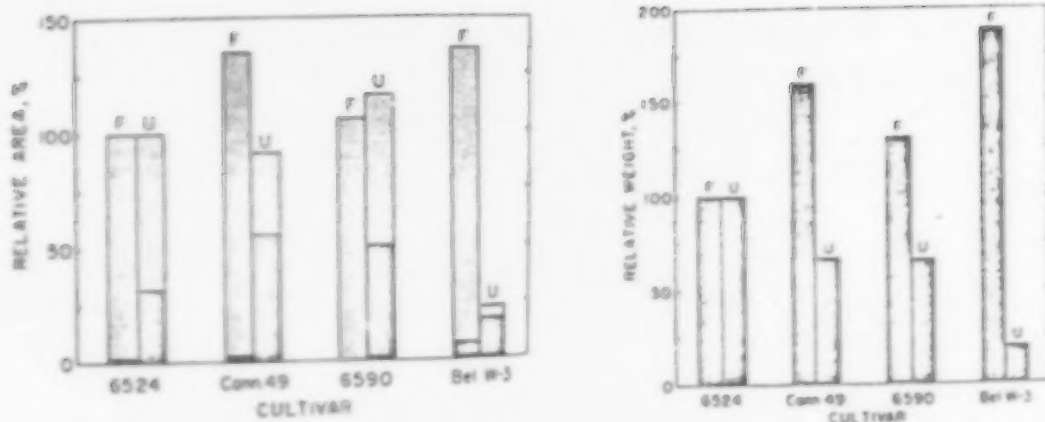
5. Relation to Other Studies

Other investigations of the relationship between oxidant exposure and injury to tobacco leaves were conducted by Menser and Heggestad (1963), Heagle and Heck (1974), Turner et al. (1972), and Taylor and Rich (1974), and covered the following topics:

- Synergistic effects of ozone and SO₂
- Predisposition of plant to ozone injury
- Comparative sensitivity of different varieties
- Effects of acute versus chronic exposure
- Protective measures against ozone exposure.

Menser and Heggestad (1966) reported a synergistic effect of sulfur dioxide with ozone, producing fleck symptoms. However, problems with the available measurement techniques at the time render their findings highly tentative. Heagle and Heck (1974) exposed tobacco plants to ozone during an eight week period and reported that exposure to ozone predisposes the plant to injury upon subsequent exposures, although it is not clear how this conclusion was reached on the basis of the reported data.

Turner et al. (1972) conducted exposure measurements in ambient and filtered (presumably ozone-free air) on four cultivars, including Bel W-3, over the entire season during a three year period. They found that, in filtered air, the ozone-sensitive Bel W-3 variety grew taller and heavier and had larger leaf area than the more ozone-tolerant varieties. In ambient air, on the other hand, the Bel W-3 variety had a significantly lower yield. With the leaf area decreasing and the amount of fleck injury increasing substantially in the unfiltered air, the resulting percentage of fleck injury for the Bel W-3 variety grew by a factor of nine from less than 10 percent in filtered air to more than 80 percent in unfiltered air. When reduction in leaf area is factored in once again to determine the total amount of usable leaf area, the total damage is assessed at 96 percent. This is illustrated in Figure 36.



Source: Turner *et al.*, 1972

Figure 36. Comparison of Leaf Area (left) and Dry Weight (right) of Several Tobacco Cultivars in Filtered (F) and Unfiltered (U) Air

The dosages to which the plants were exposed in the previous experiments during the two growing seasons can be determined, with the aid of available data on prevailing ambient oxidant levels, at 7.75 and 8.25 ppm-hours, respectively. However, Heck *et al.* (1966) showed that an equivalent damage could be produced by an acute exposure for four hours to a concentration of 0.6 ppm, for a total dosage of 2.4 ppm-hours. This indicates that an acute dosage can produce the same damage as a much larger chronic dosage and that significant damage can occur over a growing season even at ambient levels below the national air quality standard.

Finally, Taylor and Rich (1974) measured the reduction of ozone injury to tobacco resulting from treatment of the plant with systemic fungicides. Leaf fleck was measured two days after high peak ozone concentrations on both treated and untreated plants. The fungicide treatment was found to reduce fleck damage by 77 percent, although stomatal openings were not affected.

6. Conclusions and Recommendations

Without doubt, the major problem with this entire area of inquiry is the lack of coordination among the individual efforts. With disparate objectives, experimental conditions, pollutant and effect measurement techniques, and reporting styles, it becomes exceedingly difficult and frustrating to draw any comprehensive and valid conclusions which are necessary to assess total economic damages and undertake judicious corrective action. This lack of a centralized guidance and coordination appears responsible for most of the flaws explored in the preceding sections.

In spite of these shortcomings, the damage function developed by Heck et al. can be very useful in its present form and as a basis for additional research. Specific merits are listed below:

- Demonstrates a valid quantitative relationship between various exposures to oxidant levels and injury to Bel W-3 tobacco leaves
- Provides a vivid graphic illustration of the relative effects of acute and chronic exposures
- Served as a starting point for additional investigations which will eventually provide a quantitative characterization of the relationship between ozone exposure and tobacco injury and yield loss.

Consequently, the following actions are recommended:

- Establishment of guidelines and criteria for conducting research on effects of air pollutants on vegetation
- Collection of more complete data on oxidant levels in rural areas
- Development of more precise and appropriate damage measurement techniques
- Definition of the synergistic effects of pollutants, such as ozone and SO₂ and meteorological factors
- Discussion of the experimental assumptions and uncertainties in the results.

D. EFFECT OF SULFUR DIOXIDE ON CORROSION OF ZINC

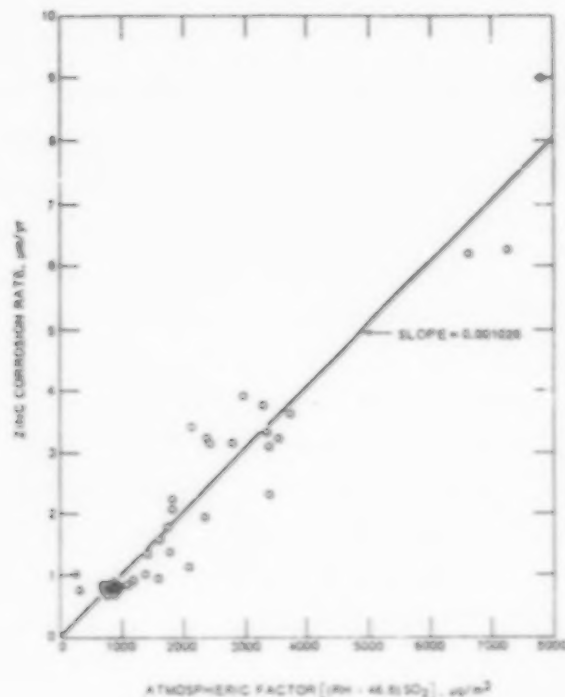
This last section analyzes the relationships between sulfur dioxide and humidity levels, on one hand, and the corrosion rate of zinc, on the other. The analysis follows the standard outline formulated in Section A.

1. Description

The importance of zinc lies primarily in its use as a coating for steel to help resist corrosion. The coating may be applied through hot dipping (galvanization) or electroplating. Corrosion of zinc and zinc-coated products accounts for a national annual loss of nearly \$1 billion. A dose-effect function for zinc-coated steel would have a definite threshold up to an exposure level corresponding to the breaching of the zinc layer, whereupon the dose-effect function for steel would govern the relationship.

The damage function selected here was developed by Haynie and Upham (1970), from results of a series of controlled experiments in eight cities over a period of up to 64 months (see Figure 37). It expresses a linear relationship between an atmospheric factor composed of SO_2 concentration and relative humidity, on one hand, and corrosion rate of zinc, in micrometers per year ($\mu\text{m}/\text{yr}$), on the other. The authors conclude that SO_2 is a major cause of zinc corrosion in a non-marine environment and that a relative humidity in excess of a value just under 50 percent is required before SO_2 attack can become effective.

The experimental procedure may be outlined as follows. Small panels of high grade 0.06 inch zinc sheet were cleaned, weighed, and exposed to ambient air. Five groups of five panels each were exposed to periods of 4, 8, 16, 32, and 64 months, in Chicago, Cincinnati, Detroit, Los Angeles, New Orleans, Philadelphia, San Francisco, and Washington. Following exposure, the panels were cleaned to remove corrosion products and weighed again to determine weight loss. The latter was then converted to corrosion rate by applying a conversion factor and dividing by exposure time.



Source: Haynie and Upham, 1970

Figure 37. Relationship Between SO_2 and Relative Humidity and the Corrosion Rate of Zinc

2. Determination of Exposure

In the case of materials damage, the distinction between dose and dosage is moot since no protective mechanisms are in operation. Moreover, the dose rate was determined not to be important for these long exposure periods by comparing results from different cities, with varying concentrations. Thus, the time factor could be incorporated in the corrosion rate, the dependent variable.

The eight urban exposure sites were generally located near the Federal Continuous Air Monitoring Program (CAMP) stations, or their state or local equivalents, and SO_2 data were obtained from these stations. The SO_2 measurement techniques at the CAMP stations were not specified in the report, but those in common use today are the colorimetric gas bubbler employing pararosaniline-sulfamic acid, for daily levels, and a conductance meter, for the hourly values. Concentrations reported in ppm were converted to $\mu\text{g}/\text{m}^3$ by applying a conversion factor of 2620 which holds approximately at 25°C .

Relative humidity above 48.8 percent was found to be a major factor in the damage produced, while temperature did not contribute substantially. The authors observed that these findings are consistent with the concept of a reaction rate controlled by the diffusion of a low concentration species to the reaction site. Relative humidity data were obtained from the weather station nearest to each exposure site.

The SO_2 concentration and relative humidity were combined into an atmospheric factor expressed as $\text{SO}_2 (\text{RH} - 48.8)$, where SO_2 is the concentration of SO_2 in $\mu\text{g}/\text{m}^3$ and RH is the percent relative humidity. The atmospheric factor does not reflect the likely effect of sulfates, but as long as the SO_2 /sulfate section remains invariate, SO_2 concentration can serve as a proxy for both compounds.

3. Determination of Effect

Corrosion of zinc by SO_2 and moisture appears to take place with the breakdown of the protective carbonate film, diffusion to the reaction site, and reaction with the metal to form a soluble zinc sulfate, which was washed away.

The effect was measured in terms of weight loss in grams, which was related to loss of thickness in micrometers by applying a conversion factor of $4.4 \mu\text{m}/\text{g}$. This permits the calculation of the useful lifetime of the $53 \mu\text{m}$ zinc coating, and hence, of the coated product. The national air quality standard for sulfur dioxide is an annual arithmetic mean of $80 \mu\text{g}/\text{m}^3$. Assuming a typical relative humidity of 65 percent, this yields an atmospheric factor of approximately 1300, which corresponds to a corrosion rate of $1.3 \mu\text{m}/\text{year}$, or a coating lifetime of 40 years.

The investigators provided sufficient replications in each exposure group to determine variance among individual samples. However, there was no indication how representative the zinc sheet used in the experiment was of the total population of zinc sheet and, more importantly, of zinc coating. Zinc coating would surely behave differently than zinc sheet, due to a different crystal structure and galvanic effects at the zinc-steel interface.

4. Validity of the Dose-Effect Relationship

The damage function in Figure 37 was derived as a simplification of one proposed by Guttman (1968). His formulation was

$$Y = k(RH - RH_0)(SO_2 + B),$$

where,

- Y = zinc corrosion rate
- RH = average relative humidity
- SO₂ = average sulfur dioxide concentration
- k = proportionality constant
- RH₀ = threshold relative humidity below which no corrosion occurs
- B = factor providing for corrosion in the absence of SO₂.

Upon being arranged for multiple regression the equation becomes

$$Y = b_0 RH \times SO_2 + b_1 RH + b_2 SO_2 + b_3,$$

where $b_0 = k$, $b_1 = kB$, $b_2 = -kRH_0$, and $b_3 = -kBRH_0$.

Results of the regression analysis show that, at the 99 percent confidence level, only SO₂ concentration and SO₂ interacting with relative humidity are statistically significant. Factoring the equation into SO₂-dependent and independent terms in the form of

$$Y = .00104(RH - 49.4)SO_2 - .00664(RH - 76.5)$$

makes this more obvious. Here it can be seen that for normal relative humidities in the range of 50-80 percent the magnitude of the last term is 0.2 or less, which can be generally considered negligible, when compared to the SO₂-dependent terms.

A second multiple regression using only the SO₂ dependent terms was performed on the equation

$$Y = b_0 RH \times SO_2 + b_1 SO_2$$

This step produced the atmospheric factor of $[(RH-48.8)SO_2]$ which is directly proportional to the corrosion rate.

The authors state that this simple relationship accounts for 92 percent of the variability of the average corrosion rates and that the more complex equation given by Guttman does not yield a better fit. Our own analysis bears out the fit of the linear equation, yielding an r-value of 0.96.

The general range of the data, and hence of the damage function, is good, because it spans both the national standard and prevalent ambient values. This permits valid interpolation of most information of potential value.

The major errors of measurement are associated with SO_2 measurements at the CAMP stations and relationship between those values and ambient levels at the exposure sites. Unfortunately, neither component error is known. Measurements of relative humidity, exposure times, and corrosion rate are considered quite accurate.

5. Relation To Other Studies

Other investigations of the relationship between sulfur dioxide levels and the corrosion rate of zinc were conducted by Guttman (1968) and Dunbar (1968), covering the effects of wetness and differential sensitivity of different grades of zinc.

Guttman (1968) was the first to report that sulfur dioxide, relative humidity, and to some extent, temperature affected corrosion of rolled zinc and laid the foundation for the Haynie and Upham study. The experimental procedure involved measurement of the time of wetness of exposed panels using a dew detector. The results showed a correlation between time of wetness and corrosion rate. Dunbar (1968) tested three grades of zinc ranging in purity from 99 to 99.99 percent and found no significant difference in weight loss at any exposure site. This suggests that the damage function in Figure 37 holds for a wide range of zinc grades, although not necessarily for zinc coatings.

Haynie and Upham (1971) investigated the corrosion rate of steel at the same site used in the zinc survey. They measured grades up to 40 $\mu\text{m}/\text{year}$, or five times the highest rate observed in the case of zinc. This substantiates their assertion that the useful life of galvanized steel ends when the zinc coating has been beached.

6. Conclusions and Recommendations

Characterization of the relationship between pollutant levels and materials damage is devoid of many of the problems that plague similar efforts in the human health and vegetation damage areas. These include the relationship between dose and dosage, control of experimental conditions, and a complex characterization of the population at risk. Some of the problems, however, remain. Thus, the damage function developed by Haynie and Upham is simple, well defined, valid, and potentially very useful. Its only major flaws are the failure to characterize the error in measurement of SO_2 levels and the relationship between corrosion rate of zinc sheet, zinc coating on steel, and uncoated steel.

Indeed, the only likely recommendations for improvement deal with these two flaws:

- Characterize errors in measurement of SO_2 levels
- Conduct a less extensive series of tests on zinc-coated steel in parallel with zinc sheet to determine the relative corrosion rates.

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V. RESEARCH NEEDS

This final chapter delineates a limited number of suggestions for additional research that were culled from the material presented in the preceding chapters. These suggestions pertain exclusively to development of dose-effect functions and do not deal with such other related and interesting topics as improvements in air quality monitoring and modeling techniques or better understanding of effect mechanisms. Successive sections address methodological improvements in determination of exposure and effect and additional dose-effect studies. Each suggestion takes the form of a brief discussion of its objectives and means of implementation.

A. DETERMINATION OF EXPOSURE

Research needs explored in this section deal with improvements in determining exposure levels and in their representation.

1. Determination of Exposure Levels

The air quality of many communities is represented by one or only a few monitoring stations. This introduces a large error in the determination of exposure levels of the target population. Additional uncertainties are brought to bear by the mobility and shielding of human subjects. The objectives of this suggestion are to:

- Determine how well air quality measurements at a monitoring station represent the ambient quality in the surrounding community
- Determine the impact of mobility and shielding of the subjects on their exposure.

These objectives could be met with the aid of a mobile monitoring station that would measure pollutant concentrations at various outdoor and indoor locations, under different emission regimes and meteorological conditions.

logical conditions. More refined measurements might be obtainable in some cases through the use of personal monitors. Some investigations of indoor air quality have already been conducted (Yocum, et al., 1971; Wade, et al., 1974).

Fulfillment of the second objective would also require calculation of a distribution of time spent outdoors for each class of the population at risk. The results of these efforts would appear in the form of confidence limits placed around specific sets of air quality data.

2. Representation of Exposure Levels

Inasmuch as most observed effects can be attributed to both long-term, low-level exposure and short-term peak concentrations, it appears reasonable that the index of exposure should account for both types of exposure. Thus, the objectives of this research suggestion are to:

- Develop an improved measure of exposure
- Explore the feasibility of translating different measures of exposure.

To this end, one could formulate a composite exposure index, such as

$$I = a + a_1 C_1 + a_2 C_2 + a_3 D$$

where a , a_1 , a_2 , and a_3 are empirically determined coefficients, C_1 and C_2 are the fractions of hours during which concentration exceeds some designated levels 1 and 2 (perhaps the primary and secondary air quality standards), respectively, and D is dosage, or the integral of concentration as a function of time.

The first phase of the suggested research would consist of replacing current exposure indices in dose-effect studies, for which adequate exposure data are available, with a composite index of the form shown above to determine whether this leads to an improved dose-effect function. Next, the accumulated knowledge would be used to explore ways of converting from one type of measure to another under different emission regimes and meteorological conditions. Such conversions would be very useful in cases where only one type of measure is available.

3. Define Monitoring Requirements

The selection of dose-effect studies today is governed at least as much by the availability of air quality data as by social needs. This is due largely to a lack of foresight by those responsible for planning and funding data collection programs. The objective of this suggestion is to remedy this situation by defining current air quality monitoring requirements for potential future dose-effect studies.

This effort would involve projection of all substantial future emission levels of likely hazardous pollutants and an estimate of the accuracy and specificity requirements dictated by future social needs and other uncertainties in the dose-effect relationships.

B. DETERMINATION OF EFFECT

Here, we take up research needs for determining the effects of air pollutants on human health and vegetation.

1. Determination of Morbidity

Morbidity in epidemiological studies is generally measured with the aid of hospital admission and occupancy and medical visit records, absenteeism from work and school, and personal diaries. The latter are considered the most accurate, but too costly and time consuming for massive studies.

The objectives of the proposed research effort would be to assess and improve the accuracy and reliability of the various methods for determining morbidity in dose-effect studies. This would be accomplished by comparing the data obtained by other means with those obtained from personal diaries for the same population to identify principal weaknesses and problems. The results of this effort would take the form of recommendations for improvements in the recording and collection of morbidity data.

2. Determination of Mortality

Mortality in epidemiological studies is expressed in terms of changes in the daily or annual death rate. However, it is not clear what this measure represents, because there is no way of knowing whether those individuals who appear to have died prematurely would have lived only a few days or many years in the absence of the pollution. The erratic behavior of mortality curves following periods of high pollution only serve to accentuate this uncertainty.

The proposed research effort would explore instead the feasibility of determining changes in life expectancy by comparing ages at death of age-adjusted populations exposed to different levels of air pollutants. As in other valid epidemiological studies, all other important covariates would have to be carefully controlled as well. The ultimate results of such an effort would be a demonstrated method for determining changes in life expectancy associated with exposure to a given pollutant for a well-characterized population group. (Takacs, 1974.)

3. Effects on Vegetation

Studies of effects of air pollutants on vegetation are characterized by a wide array of measures of effects. This frustrates any attempts at aggregating results of different studies over pollutants, plant species, geographic regions, or effects, and hampers the drawing of general conclusions about the dose-effect relationships.

The objective of the proposed effort would be to provide uniform guidance for experiment design, data collection, control of cofactors, measurement of effects, and display of results and the associated uncertainties. Such a study would obviously require the participation and endorsement of a wide spectrum of respected investigators in this field.

C. STUDY DESIGN

There are a number of lively controversies surrounding the design and development of dose-effect functions. Several of the more important are taken up below.

1. Cost-Effectiveness of Epidemiological Studies

In light of the large uncertainties characterizing the results of epidemiological studies, some people have suggested their replacement by more precise, though also much more costly, efforts. One such suggestion is Lester Lave's "dream study," which would focus on carefully selected sample populations in a number of cities. The selected individuals would be monitored to determine their personal exposure to all important environmental factors, including air pollutants, radiation, and weather conditions, and they would keep diaries recording their symptoms. (Morris and Morgan, 1974.)

The objective of the proposed project would be to assess the relative cost effectiveness of an epidemiological study and Lave's "dream study" for the more important pollutants and effects. Such an effort would need to take into account the timing and accuracy requirements of the intended uses of the results and would specify the conditions when one type of study is preferable to the other.

2. Estimation of Dose-Effect Relationships

A number of dose-effect studies have been excluded from consideration in our survey of the literature in Chapter II because of various flaws ranging from insufficient data to inadequate consideration of covariates, or use of improper statistical methods. This proposed research project would attempt to correct this situation by providing a manual for estimating dose-effect relationships.

Such a manual would define the preferred and optional statistical procedures to be followed for various sets of constraints and requirements. It would specify various methods of presentation of results and the associated errors and uncertainties. In effect, the manual would constitute a greatly expanded, reorganized, and more scholarly version of our Chapter III.

D. ADDITIONAL DOSE-EFFECT STUDIES

In addition to the methodological research needs outlined in the preceding sections, a number of important dose-effect functions still remain to be developed. These are defined here for the three major target areas.

1. Health Effects

The more important air pollution dose-effect relationships that need to be developed or validated may be listed as follows:

- Effects of NO₂ and nitrates
- Effects of different types of sulfates (e.g., metal, acid, salts)
- Chronic effects of low-level (below standards) exposures to various pollutants

- Carcinogenic, teratogenic, and mutagenic effects of air pollutants, as specified in Section 103(f)(2)(B) of the Clean Air Act of 1970.

2. Effects on Vegetation

Effects of air pollutants on vegetation appear much more widespread than had been heretofore suspected, especially in light of the recent discovery of high oxidant levels in rural, crop-growing areas. Yet past studies of growth reduction and yield loss exhibit widely varying results. Consequently, the following types of dose-effect relationships appear to be urgently needed.

- Effects of oxidants on yields of major crops
- Synergistic effects of sulfur oxides and oxidants
- Long-term effects of pollutants on ecological balance.

3. Other Effects

Other areas that deserve additional study are:

- Effects of various air pollutants on paints, cement, rubber, plastics and wood
- Effects of various air pollutants on aesthetic appreciation of an area, including visibility
- Effects of various air pollutants on climate and local weather conditions.

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APPENDIX. DEMONSTRATION OF THE INTERPRETIVE UTILITY
OF AIR POLLUTION DAMAGE FUNCTIONS

This appendix contains a brief demonstration of specific uses of damage functions, prepared for inclusion in the Environmental Conditions and Trends Chapter of the CEQ 1975 Annual Report. The primary objective is to show how air pollution damage functions can serve as interpretive aids in communicating the significance of recently measured air quality trends to persons who lack advanced technical training.

The report begins with an introduction to the concepts of pollution damages and benefits, the nature of air quality trends, and the application of damage functions. The remainder of the presentation takes up the utility of three damage functions and their relationship to air quality trends. These functions define the impact of sulfur dioxide on human health, oxidant injury to tobacco leaves, and effect of sulfur dioxide on corrosion of zinc.

A. INTRODUCTION

This section introduces the concepts of damages and benefits associated with environmental pollution, as well as the nature of air quality trends and utility of damage functions. The actual demonstration of the utility of several damage functions is taken up next.

1. Environmental Damages and Benefits

Nearly everyone is now convinced that there exists a causal relationship between environmental pollution levels and certain damages suffered by society. These may take the form of increased mortality and incidence and prevalence of disease, diminished enjoyment of the outdoors, reduced crop yields, more frequent maintenance and replacement of exposed materials, and other, less well-identified losses. This being the case, a reduction in pollution levels should bring about a corresponding decrease in these damages and yield a set of benefits equivalent to the difference in damages before and after the reduction took place. If the damages are reduced to the point at which they are no longer observed, then the benefits realized are equal to observed damages.

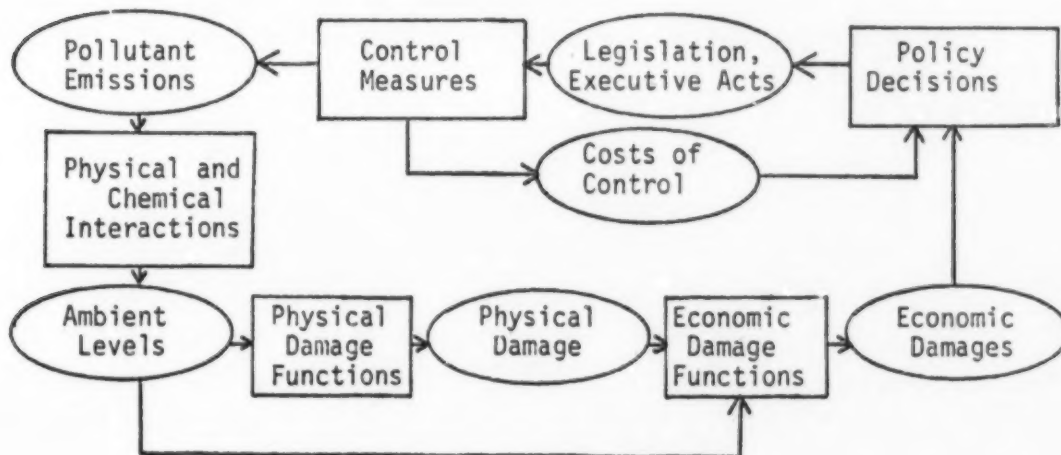
Legislators, planning officials, and other environmental decision makers are frequently faced with the decision of how much to reduce pollutant levels in the light of the associated direct costs of pollution control and possible secondary economic effects. In the past, these decisions were rather obvious and they were made in response to popular sentiment. However, with the passing of time, these costs became more acutely felt, especially in the wake of the energy crisis, while the beneficial effects of reduced, or at least stable, pollution levels were neither obvious, nor easily measured. Clearly, the decision makers would need a more sensitive tool for comparing and trading off the costs and benefits of various levels and types of pollution control. Indeed, this need gave birth to the science of environmental benefit/cost analysis.

Admittedly, benefit/cost analysis is not an exact science, primarily because social benefits and costs are diffuse and frequently

difficult to express in monetary terms. Even so, the process of logical and systematic scrutiny inherent in benefit/cost analysis can contribute substantially to the ability of decision makers to improve the social welfare through more efficient allocation of the limited resources of the public treasury.

There is an interactive relationship among pollutant emissions, ambient air quality, damages and benefits, and policy decisions. This is illustrated in the diagram below, where rectangles indicate processes and actions, whereas ellipses represent their products. The pollutants emitted by stacks, automobile exhaust pipes, and other sources undergo physical and chemical interaction in the atmosphere under the influence of meteorological factors to yield prevailing ambient pollutant levels. The resulting physical or biological damages are converted into some realistic economic terms and traded off against the costs of controls to guide decision makers on the extent and type of controls to be applied. Alternatively, economic damages can be determined directly as a function of ambient levels through surveys of property values, declared willingness to pay, legislative decisions, and litigation awards.

This is an adaptive process, with major decisions made at first on the basis of fragmentary information and successive refinements applied, as the constraints and implications of each step become better known. The transition between pollutant emissions and resulting damages is of special interest here and is taken up in more detail in the next two sections.



2. Ambient Levels and Trends

As was mentioned earlier, ambient pollutant levels are determined by physical and chemical interactions of pollutant emissions in the atmosphere under the influence of such meteorological factors as wind, precipitation, sunlight, and temperature. The most important mechanisms are dispersion and dilution of pollutants by air movement, as well as the formation of photochemical oxidants by various combinations of pollutants, including nitrogen dioxide and hydrocarbons, under the influence of the sun's ultraviolet radiation. Other important interactions with meteorological factors result in the oxidation of sulfur dioxide and nitrogen dioxide to the more hazardous sulfates and to nitrates, respectively, the entrapment of pollutants near the earth's surface by thermal inversions, and the cleansing of the air by falling rain drops.

Attempts to predict ambient levels on the basis of the nature and location of pollutant emissions and analytical models of the various physical and chemical interactions have been only partially successful. Consequently, many investigators have chosen to rely on measured ambient levels, or more recently, on air quality trends. These trends express the magnitude and direction of change in ambient levels of specific pollutants as a function of time, and they have several important advantages over measurement of ambient levels. In the first place, they provide the only valid indicator of the relative success of pollution control action, as well as some predictive measure of future damages associated with various levels of exposure to specific pollutants. Secondly, they tend to be more reliable than ambient measurements, because some errors of measurement may cancel out.

Comprehensive assessment of national air quality trends has become feasible only recently, in the wake of the requirement by the Clean Air Act of 1970 that each state collect and report specific air quality data. Air quality data for the five air quality standard pollutants (total suspended particulates, sulfur dioxide, carbon monoxide, oxidants, and nitrogen dioxide) are supplied by Federal, state, and a number of local agencies to the EPA National Aerometric Data Bank (NADB), where they are

validated and consolidated. With the aid of these data, the EPA Office of Air Quality Planning and Standards has been able to publish in August 1973 the first annual Air Quality and Emissions Trends report, which analyzed nationwide emission trends between 1940 - 1971, and trends in ambient levels for more recent years. This document was subsequently supplemented by the 1972 and 1973 editions of Monitoring and Air Quality Trends Report, published in December 1973, and October 1974, respectively, which focused on recent ambient level trends for the nation's 247 air quality control regions. These reports concluded that ambient levels of sulfur dioxide, total suspended particulates, and other pollutants in urban areas have been decreasing in response to pollution control measures.

However, any interpretation of ambient level measurements, and hence of air quality trends, needs to be tempered by an appreciation for the serious limitations of present data collection practices. These may take the form of number and location of monitoring stations, measuring instrumentation, and data collection and processing. The location of air quality monitoring stations is somewhat erratic and is frequently dictated by expediency and convenience, rather than by the more fundamental considerations of proximity to pollution sources, meteorological patterns, or target populations. Moreover, a number of urban and most rural areas have insufficient coverage for specific pollutants, such as nitrogen dioxide or oxidants. This is especially troublesome in light of the recent discovery of high oxidant levels in rural areas and the resultant effects on crop yield.

Even more importantly, there are currently no direct and specific methods for measuring such important pollutants as nitrogen dioxide, nitrates, and sulfates. Thus, indirect techniques, subject to errors and assumptions, must be used. In some cases, past methods have been modified or altogether discontinued, destroying the continuity of air quality records. Finally, even where optimal levels of station coverage and sophistication of measurement pertain, one must still balance the sampling frequency and the resultant cost of data collection, storage, and processing with the budgetary constraints and potential utility of the data.

The next major step in the transition between emission levels and damages is the damage function, which relates ambient levels to resultant physical and economic damages.

3. Damage Functions

A damage function is the quantitative expression of a relationship between exposure to specific pollutants and the type and extent of the associated damage to a target population. Exposure is typically measured in terms of ambient concentration levels and their duration and it may be expressed as "dosage" or "dose". Dosage is the product of the time and ambient concentration to which the subject has been exposed, while dose, represents that portion of the dosage that has been instrumental in producing the observed damage (e.g., the amount of pollutants actually inhaled in the case of health effects of air pollution).

The damage can become manifest in a number of ways and can be expressed in either physical and biological, or economic terms. If the effect is physical or biological, the resultant relationship is known as a physical or biological damage function, or a dose-effect function. In an economic damage function, on the other hand, the effect is expressed in monetary terms. Economic damage functions can be developed by assigning dollar values to the effects of a physical or biological damage function, or by direct correlation of economic damages with ambient pollutant levels.

In reporting a damage function, one needs to specify the pollutant, the dose rate, the effect, and the target population, or the "population at risk". Dose rate, or the rate at which ambient concentration varies with time, has a major influence on the nature and severity of the resultant effect. Long-term exposure to relatively low concentrations of air pollutants may result in manifestations of chronic disease, characterized by extended duration of development, delayed detection, and long prevalence. Short-term exposure to high concentration levels, on the other hand, may produce acute symptoms, characterized by quick response and ready detection, as well as chronic, cumulative, or delayed effects.

Specification of the population at risk involves the characterization of the nature and magnitude of the exposed population. It is crucial to this exercise for several reasons. First, it serves to define the total damages produced by a given level of exposure by multiplying the corresponding unit damage (e.g., increased mortality) for the specified population at risk (e.g., white males over 65) by the total number of units within this population. Secondly, it permits investigators to adjust their results to reflect the influence of various intrinsic (e.g., age, race, sex) and extrinsic (e.g., general health, occupation, income and education) variables in assessing the specific effects of air pollutants (e.g., increased incidence of lung cancer). Finally, it can provide useful guidance for allocating air pollution control resources by identifying areas with particularly susceptible populations exposed to relatively hazardous levels of pollutants.

A typical S-shaped damage function, showing the damage corresponding to a given exposure to a specific air pollutant, is presented in Figure A-1. The ordinate may represent either the number of individuals affected or severity of effect. The abscissa indicates the dosage in terms of time, at a given ambient concentration, or in terms of ambient concentration for a fixed period of time. The lower portion of the curve suggests that, up to a certain exposure value, known as a threshold level, no damage is observed, while the upper portion indicates that there exists a damage saturation level (e.g., death of the target population or total destruction of the crops), beyond which increased exposure levels do not produce additional damage. The middle, quasi-linear portion is very useful in that any data points here can be readily interpolated, and the frequent assumption about linearity of a damage function is most valid in this sector.

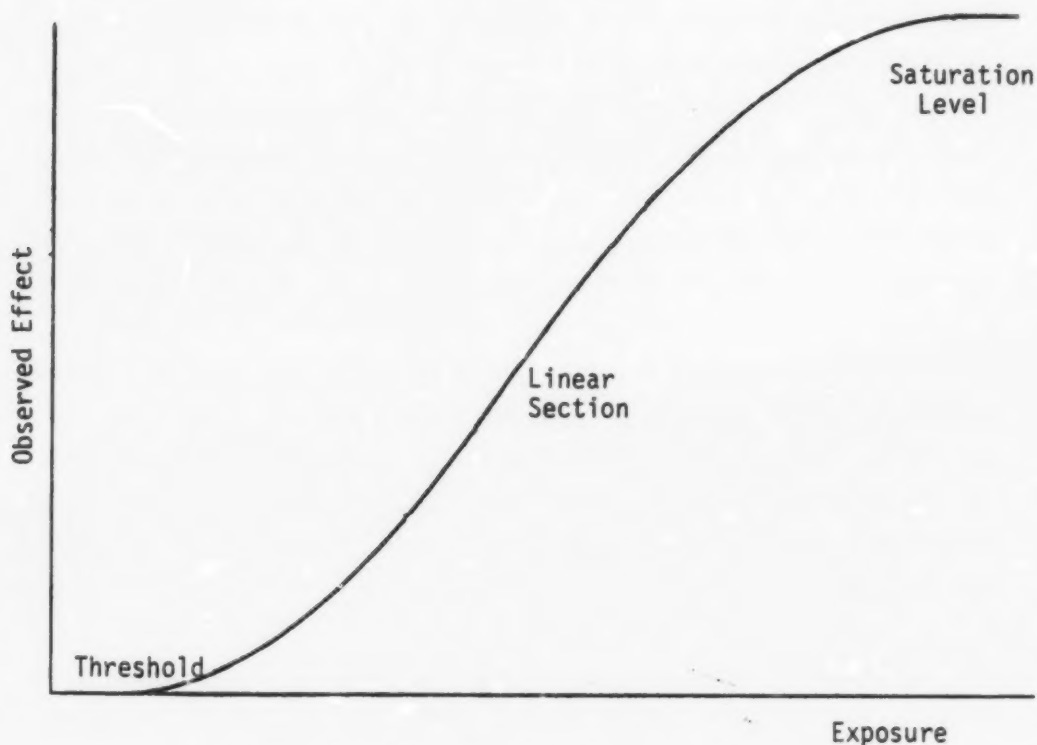


Figure A-1. Hypothetical Damage Function

The data required to develop physical or biological damage functions are obtained primarily through epidemiological, field, clinical, toxicological, or laboratory investigations. The first approach involves the comparative examination of the effects of pollutants on selected segments of population exposed to different levels of pollution, in order to deduce the nature and magnitude of the likely effect. Field observations represent a similar approach to assessment of effects on animals, vegetation, and materials, and they are characterized by similar analytical techniques and concerns. Clinical studies are based on hospital observations of the results of exposure on human subjects. Toxicological investigations involve deliberate administration of controlled doses of pollutants to animal, and occasionally, human subjects, and observation of the resulting effects. Laboratory studies represent essentially the same approach for determining effects of pollutants on plants and materials.

Several considerations need to be noted about epidemiological and field studies. First, it is very important to remove or control the

influence of the various intrinsic and extrinsic variables cited above that may be responsible for the different effects observed. Secondly, epidemiological and field studies and observations can show only an association between exposure to pollution and the observed effect, suggesting the existence of a causal relationship. Such a relationship can be then tested, by toxicological and laboratory studies. It can be rendered plausible by the presentation of a plausible connective mechanism, or other weight of reason.

The common practice of setting air quality standards at, or just below the corresponding threshold levels has engendered considerable controversy. Since threshold levels are largely contingent on our ability to observe and measure small degrees of damage in large populations, they become continually eroded with improving state of the art in damage assessment. Moreover, it is known that low levels of certain pollutants which are incapable of producing measurable damages, nevertheless generate a predisposition to subsequent damage. Thus, the proponents of reduced standards advocate that these be set at 1-3 orders or magnitude below threshold levels, depending on the gravity of the corresponding damage, to ensure public safety. Opponents, on the other hand, argue that the economic costs and other deprivations associated with controls required to achieve such low standards cannot be justified.

B. DEMONSTRATION OF DAMAGE FUNCTIONS

Following this brief overview of the nature of air quality trends and damage functions, we now proceed to illustrate some of the concepts introduced and to demonstrate the interpretive utility of damage functions. These functions have been selected in the areas of health effects, vegetation injury, and material corrosion. A discussion of the function selection process precedes the presentation of the functions.

1. Selection of Damage Functions

Most damage functions in the area of human health effects are developed on the basis of epidemiological studies, which require a very substantial effort to identify a degree of damage corresponding to a given exposure to a certain air pollutant over a specified period of time. The results of this effort may represent only one point toward the construction of a damage function for that specific health effect pollutant, dose rate, and target population. The results of other studies can contribute additional points to the construction of the same curve only if these specific conditions are sufficiently similar. Thus, one can readily appreciate that health effects damage curves are typically sketchy and unreliable.

There have been attempts to ameliorate this situation with the aid of clinical observations and toxicological investigations. Thus, a recent report for EPA by the California Air Resources Board formulated several hundred health effect damage functions on the basis of pooled expert opinions by a team of medical specialists. Toxicological investigations have been conducted on animals and, in case of the less hazardous pollutants, on human subjects. Both of these approaches involve major assumptions about the dose rate, applicability of effects on animals to human subjects, and other factors, and must be interpreted with great care.

The situation should be slightly improved in assessing damages to animal health and vegetation, because of the greater opportunity to conduct controlled experiments. It should be even better in assessing

material damage, because of the additional ease of characterizing the target population. Unfortunately, the required research has not been carried out.

Three major criteria were employed in selecting the several damage functions for the present demonstration:

- Availability of air quality trend data
- Availability of sufficient exposure-damage data
- Importance of damage

The exposure-damage data must be sufficient to construct even a rudimentary damage function. Importance of damage is measured in terms of the total loss to society, including both economic and social values.

The following functions were selected:

- Sulfur dioxide - human mortality
- Ozone - injury to tobacco leaves
- Sulfur dioxide - corrosion of zinc

Sulfur dioxide levels have been widely correlated with human health effects and the nature of this relationship has received considerable attention. The vast impact of ozone on crop yield and quality has been recognized as a result of recent discovery of high oxidant levels in rural areas and a number of yield loss experiments. Corrosion of metals is the most important component of material damages and zinc-coated steel is widely used in articles exposed to the atmosphere.

2. Effects of Sulfur Dioxide on Human Mortality

Sulfur dioxide (SO_2) was one of the first pollutants to be implicated in human health effects, and a number of investigators have sought to define its impact on human morbidity (incidence and prevalence of disease) and mortality rates. More recently, there have been indications that SO_2 has been only a proxy for a more damaging agent -- suspended sulfates (the sulfate fraction of particulates), and/or a third factor closely associated with sulfates, such as inert particulates or humidity. EPA has evolved a mathematical model of the relationship between SO_2 and

sulfate levels by comparing their values in several cities. However, it should be noted that the actual relationship varies substantially among individual areas.

A composite plot of the relationship between daily sulfur dioxide levels and percent change from the mean of daily mortality rate, based on the results of two New York City studies, is shown in Figure A-2. The data appear to fall on the linear portion of the curve, and it is not clear where or whether a threshold level exists. Mortality rate changes appear both below and above the mean death rate, depending on variations of SO_2 levels with respect to the value assumed in establishing the mean death rate.

It is rather easy to find fault with the function in Figure A-2. For one thing, it attempts to correlate daily values of death rate and sulfur dioxide level, although some sort of lag time must surely be involved. It supplies no information on the many days of discomfort, disability, and other losses that obviously preceded death. It provides no characterization of the cause of death or of the population at risk, not even age, or general state of health. Yet, for all that, the function is very useful, for it provides a crude empirical estimate of the consequences of alternative pollution control actions, as well as a starting point for additional research in this area.

In addition to changes in mortality rates, air pollutant levels have been correlated with increased incidence, prevalence, and severity of various respiratory and other disorders. In particular, the aggravation and prevalence of asthma attacks by suspended sulfates at several temperature levels have been investigated by EPA's CHES (Community Health and Environmental Surveillance System) program in a number of urban areas. Plots of this relationship for Salt Lake City and New York City are shown in Figure A-3. Unfortunately, the lack of national trend data on suspended sulfates and the uncertain relationship between sulfur dioxide and suspended sulfate levels preclude the use of these functions for interpreting the significance of air pollution trends.

The curves in Figure A-3 are known as "hockey stick" functions, because of their shape, which attempts to approximate the lower and

middle portions of the classical S-curve in Figure 1. It should be noted that these plots allege the existence of a very pronounced threshold at the sulfate concentration corresponding to the intersection of the two lines. The corresponding asthma attack rate is that level which would be found even in the absence of sulfur dioxide pollution.

The trends for sulfur dioxide levels are well established and a plot of annual mean concentration in urban areas for the period 1964-1973 is presented in Figure A-4. It may be noted that SO_2 levels during that period decreased by 50 percent, from 50 to 25 $\mu\text{g}/\text{m}^3$, although individual urban areas exhibited substantial variations. According to the plot in Figure A-2, this corresponds to a 0.3 percent reduction in the mean death rate. Alternatively, if SO_2 levels were allowed to climb to the primary standard of 80 $\mu\text{g}/\text{m}^3$, one would expect an 0.5 percent increase in the death rate.

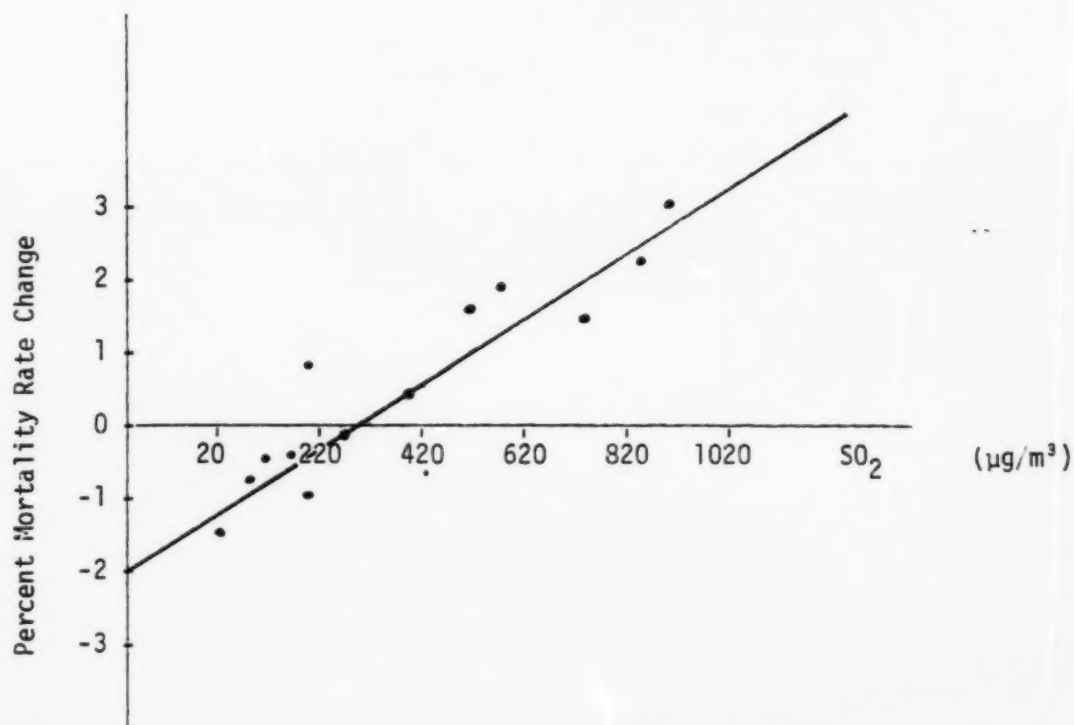


Figure A-2. Relationship Between Daily Sulfur Dioxide Levels and Daily Mortality Rates in New York City Metropolitan Area (based on Glasser and Greenberg, 1971; Buechley, 1973)

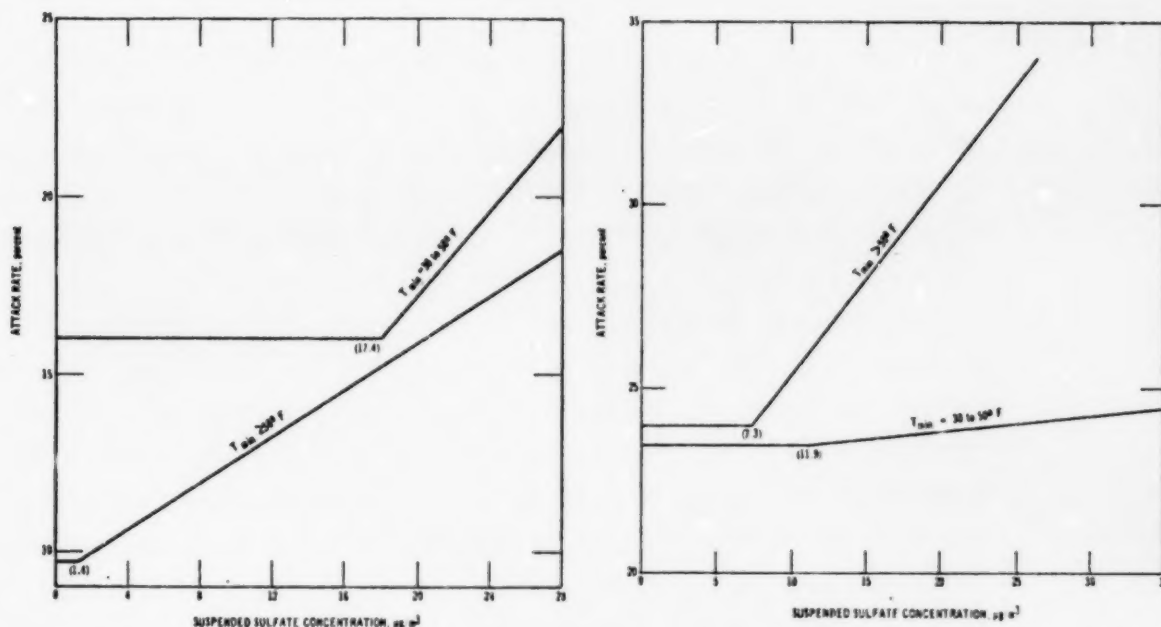


Figure A-3. Effect of Minimum Daily Temperature and Suspended Sulfates on Daily Asthma Attack Rates in Salt Lake (left) and New York (right) areas. (EPA, May 1974)

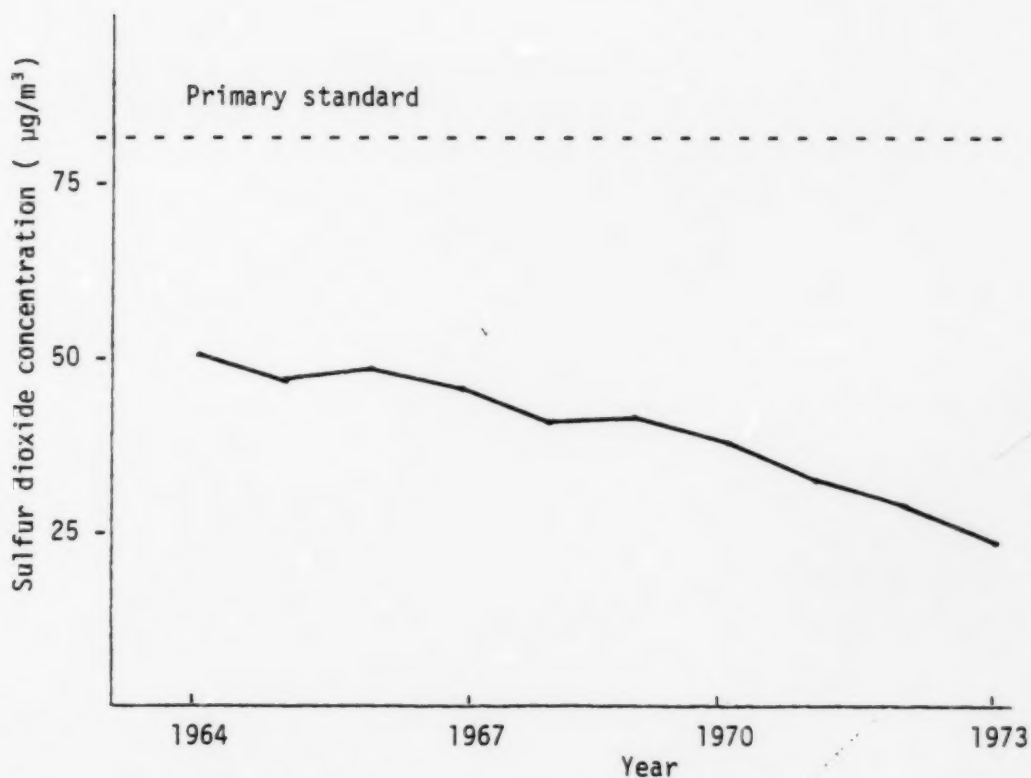


Figure A-4. National Trends of Sulfur Dioxide Levels (Annual Arithmetic Means) for 1964-1973. (Adapted from EPA, August 1973; EPA, October 1974)

There are several ways of interpreting changes in the death rate. The first logical step is to translate them into the corresponding increases or decreases in the number of deaths. Since the total annual number of deaths in the U.S. is just under 2 million, 0.3 and 0.5 percent changes in the death rate correspond to 6,000 and 10,000 annual deaths, respectively.

However, a single factor, such as air pollution, cannot be held responsible for people's deaths, but only for their premature deaths. Clearly, people would still be dying in the absence of air pollution, though hopefully at a more advanced age. Thus, the key question here is the change in life expectancy resulting from a specific change in SO_2 levels. Once this has been established, one can apply such economic factors as loss of productive days and costs of medical and hospital care, to compute the resultant damage to society.

3. Effects of Oxidants on Tobacco Leaves

Interest in the effects of oxidants on vegetation has been aroused recently by the discovery of high oxidant levels in rural areas and by the publications of results of controlled experiments revealing unexpectedly high yield losses attributed to oxidant exposure. In fact, EPA's draft 1975 report on the Cost of a Clean Environment places the estimate of 1973 crop losses due to high oxidant levels at nearly \$3 billion.

Indications of high rural oxidant levels were discovered in 1970 by EPA in the course of investigating injury to Christmas trees. Subsequent readings in rural areas of California, Florida, Maryland, New York, Ohio, Pennsylvania, West Virginia, and Wisconsin, confirmed that the one-hour standard of 0.08 ppm was being exceeded frequently during the summer months. Experiments by at least a dozen teams of investigators cited in the EPA report, comparing scores of protected and exposed species of crops revealed yield losses as high as 60-70 percent at these ambient levels.

Reasonable damage functions have been developed for several plant species, such as the Bel-W₃, a sensitive variety of tobacco, which is a major agricultural crop in the southeastern states. A damage function

relating exposure to oxidants, with leaf injury, an important measure of damage for the tobacco plant, was developed by Heck et al. and is pictured in Figure A-5. It may be noted that this graph provides separate plots of both the concentration and time elements of exposure, permitting the interpretation of both acute and chronic effects.

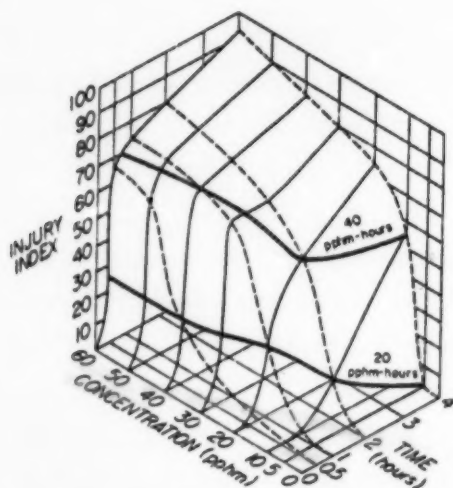


Figure A-5. Relationship Between Oxidant Exposure and Injury to Tobacco Leaf (Heck et al., 1966)

Although data on oxidant level trends in rural areas are very scarce, the graph permits speculation on the likely effects of changes in pollutant levels on the injury to tobacco leaves. For example, one can learn that, for one-hour exposures, a decrease in ozone level from 0.5 to 0.3 ppm (50 to 30 pphm) would reduce the injury index by 10 (from 73 to 63), while for one half-hour exposures, such a decrease would produce a reduction of 50 (from 62 to 12). This variation of the effect of a given dose with dose rate can be seen clearly by noting the variations of the 20 and 40 pphm-hrs plot with respect to injury index.

For all its sophistication and utility, there is much that this graphic representation does not report. There is no characterization of long-term effects of low-level exposures, though recent studies have indicated the likelihood of significant damage by prolonged exposure to levels below 0.1 ppm. Similarly, there is no information on how the impact would vary with age of the plant, an important aspect of the

characterization of the population at risk. Finally, one would like to know the relative impact of other environmental variables, such as relative humidity, temperature, and sunlight.

4. Effect of Sulfur Dioxide on Corrosion of Zinc

Corrosion of metals is the most substantial component of air pollution damage to materials, accounting for over \$1.6 billion in 1973. Steel, in turn, is the most widely used metal and, in many applications involving exposure to the atmosphere, steel is coated with zinc by the galvanizing process. Thus, zinc was a likely choice for illustration of pollutant damage to materials.

Once the zinc coating has been breached, the corrosion rate of the underlying steel proceeds much faster. This is due in part to the higher reactivity of steel, but also to the galvanic potential generated at the interface between the two metals.

The corrosion rate is usually influenced by humidity and temperature, as well as by sulfur dioxide. Hence, the damage function, developed by Haynie and Upham (1970) on the basis of a series of controlled experiments and shown in Figure A-6, expresses the corrosion rate of zinc as a function of an atmospheric factor, formed as a product of SO_2 concentration and a modified value of relative humidity. Thus, changes in the atmospheric factor are directly proportional to variations in sulfur dioxide levels.

For example, the 50 percent decrease in SO_2 levels between 1964 and 1973, as noted in Figure A-4, should have reduced corrosion rates from 0.8 to 0.4 μm per year, thus doubling the life expectancy of zinc surfaces.

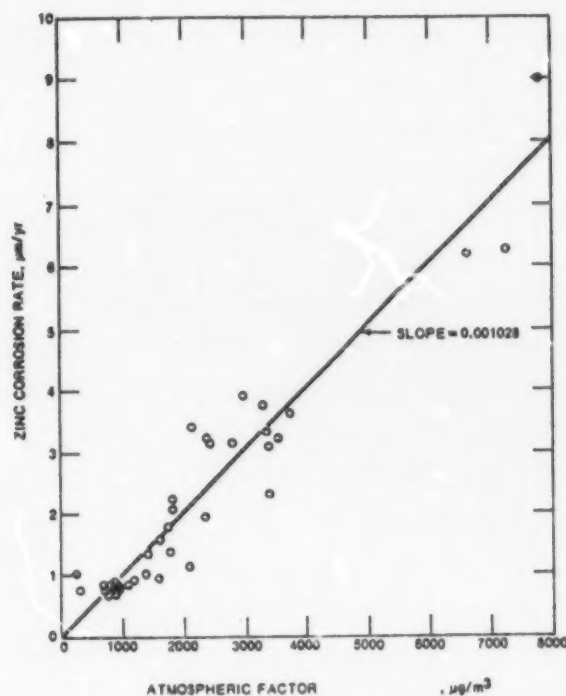


Figure A-6. Effect of SO_2 and Relative Humidity on the Corrosion Rate of Zinc (Haynie and Upham, 1970).

C. CONCLUSIONS

In spite of the large amount of effort that has been devoted to development of air pollution damage functions and compilation of air quality trends, it is fair to say that this vast, new, and promising area of investigation has been barely breached. The additional effort needed has been outlined in the introductory discussion and in the illustrative examples cited above. The potential return is impressive indeed. It promises nothing less than to provide public officials with an effective tool for allocating efficiently limited resources among the many conflicting demands for pollution control and other aspects of social welfare.

D. REFERENCES

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